AN L-BAND TUNNEL DIODE OSCILLATOR

(Including L-Band Transistor Oscillator-Multipliers)

FINAL REPORT

1 June 1962 through 31 December 1964

The objective of this program was to develop a tunable tunnel-diode oscillator giving 25 milliwatts power output in the frequency range 1660 to 1700 megacycles. The oscillator was to be designed for minimum production cost and to be adaptable to radiosonde applications. A modification of the contract added the development of 250 mw L-Band Transistor-Oscillator-Multipliers.

Contract No. DA36-039 SC-90773

DA Project No. 1P6 22001 A 056

prepared for

U.S. ARMY ELECTRONICS LABORATORY
Fort Monmouth, New Jersey

by

RADIO CORPORATION OF AMERICA
Electronic Components and Devices
Microwave Tube Operations Department
Harrison, New Jersey

RADIO CORPORATION OF AMERICA
ELECTRONIC COMPONENTS AND DEVICES
HARRISON, NEW JERSEY 07029

May 25, 1965

Subject: Contract DA36-039 SC-90773
Final Report
1 June 1962 through 31 December 1964

Dear Sir:

Enclosed is the number of copies of the subject report that we have been asked to send you as shown in the Distribution List issued by the U.S. Army Electronics Research and Development Laboratory. The list is bound in the report.

Very truly yours,

A. Leigh Balber

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Microwave Engineering
Technical Publications

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Enc.

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Report Prepared By

D. E. Nelson
R. Gold
E. T. Casterline

Report Approved By

F. Sterzer

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SECTION I

PURPOSE

A. TUNNEL DIODE OSCILLATORS

The original objective of this program was the development of a tunnel-diode oscillator capable of a power output of 25 milliwatts over the tunable frequency range of 1660 to 1700 megacycles. Other requirements include a minimum production cost design, development of solid state modulator circuitry and capability of meeting various environmental requirements.

The program included the following:

1. Development and fabrication of suitable tunnel diodes.
2. Development of tunable oscillator circuits.
3. Development of modulation techniques and circuits.
4. Testing of tunnel-diode oscillator units to electrical and environmental specifications.
5. Construction for delivery of 1 breadboard oscillator unit, 3 prototypes and 6 developmental models.

The major objective specifications were:

1.	Power Output (over 1660-1700 Mc tuning range)	25 mw min.
2.	Ambient Temperature Operation -55°C to 75°C	
	Power Output	25 mw min.
	Frequency change	±2 Mc max.
3.	Frequency change for ±10% supply voltage change	±2 Mc max.
4.	Frequency Modulation - frequency shift	300 kc ±25 kc

At a later date the contract was modified to include ruggedized tunnel diode oscillators suitable for a gun probe sonde application of the Ballistic Research Laboratories of the Aberdeen Proving Grounds. However, shortly after

the modification it was determined that 25 mw of power would be insufficient for this application and 100 to 250 mw would be required. Since this power level seemed impractical from tunnel-diode oscillators, RCA proposed development of a transistor-oscillator-multiplier for this application.

B. TRANSISTOR-OSCILLATOR-MULTIPLIERS

1. Gun Probe Sonde

The objective of this phase of the program was the development of a transistor-oscillator-multiplier giving 250 mw rf power output and capable of withstanding 50000 g acceleration. Included in the program was the fabrication and delivery of two breadboard units and three ruggedized units. The major specifications included

Frequency	1750 ± 10 Mc
Power Output	250 mw min.
FM Modulation frequency deviation	±125 kc
Nonoperating acceleration	50000 g

2. Standard Radiosonde Transistor-Oscillator-Multiplier

Due to the excellent results on the Gun Probe Sonde transistor-oscillator-multipliers and also to the difficulty in temperature compensating the tunnel-diode oscillators,RCA suggested that the final three developmental models of the standard radiosonde units be changed from tunnel-diode oscillators to transistor-oscillator-multipliers. This suggestion was accepted and the objective specifications were the same as listed under Section A above except the power output was increased from 25 mw to 250 mw.

SECTION II

ABSTRACT

A. TUNNEL-DIODE OSCILLATORS

Gallium-Arsenide tunnel diodes having 600 ma peak current and resistive cutoff frequencies of 6 to 10 Gc were developed. The diodes were fabricated in a low inductance package permitting operation at L-band at power outputs up to 30 mw.

Low impedance oscillator circuits were designed which gave power outputs of 20 to 30 mw over the required 1660 to 1700 Mc tuning range. A transistor current regulator circuit was developed which permitted operation of the oscillators with ±10% supply voltage variation with a frequency change of ±2 Mc or less. Modulator circuitry for frequency modulating the oscillator was developed.

It was not possible, however, to meet the requirements of less than ±2 Mc frequency variation over an ambient temperature range of -55°C to +75°C. Although the current regulator could be compensated to maintain nearly constant current, the change in frequency of the oscillators at constant current was so great that temperature compensation appeared to require an extensive effort. For this reason RCA suggested that the final three developmental models be transistor-oscillator-multipliers.

B. TRANSISTOR-OSCILLATOR-MULTIPLIERS

1. Gun Probe Sonde

A transistor-oscillator-multiplier was developed using the RCA type 2N3553 overlay transistor simultaneously as a 437 Mc oscillator and as a variable capacitance frequency quadrupler. The device gives a 1750 Mc power output of 100 mw

at 15 volts supply voltage or 250 mw at 20 volts. The TOM may be frequency modulated at frequency deviations up to 2 Mc by applying a small voltage to the base of the transistor.

One TOM unit was acceleration tested by the Ballistic Research Laboratories. The unit performed satisfactorily with little change in characteristics after being fired at 15000 g acceleration. After a second firing at 37000 g, however, the unit failed due to the opening of one of the leads in the transistor. A small number of the transistors had previously tested satisfactorily after being fired at 50000 g. Further tests of both transistors and TOM units will be required to determine the acceleration capability. Two additional TOM units have been delivered to BRL for testing.

2. Standard Radiosonde Units

Typical transistor-oscillator-quadrupler units gave 300 to 400 milliwatts of power at 10% efficiency over the 1660 to 1700 Mc tuning range. The frequency change with a ±10% supply voltage change was about 10 Mc. A simple series transistor voltage regulator reduced this change to less than 1 Mc. Positive temperature coefficient resistors and negative temperature coefficient capacitors were used to temperature compensate the unit reducing the frequency variation over a -55°C to +75°C from 25 Mc or greater to less than 4 Mc. The units can be frequency modulated at frequency deviations up to 2 Mc by a small voltage applied to the base of the transistor. The pulling figure for 1.5 VSWR was 2 Mc or less for all units tested.

SECTION III

PUBLICATIONS, LECTURES, REPORTS AND CONFERENCES

There were no publications or reports issued during the period of this contract.

A paper entitled "Transistor-Oscillator-Multipliers" written by D. E. Nelson, H. C. Johnson and H. P. Mierop was presented by D. E. Nelson at the 1964 Electron Devices Conference in Washington, D. C. on October 31, 1964.

The following conferences were held on the contract:

September 9, 1962 - General Discussion and Review of Contract at RCA Laboratories, Princeton, New Jersey.

Present: Ivan L. Chase - U.S.A. E.R.D.L.
G. Hambleton - U.S.A. E.R.D.L.
E. McCormick - U.S.A. E.R.D.L.
E. Dowski - U.S.A.E.R.D.L.
D. Nelson - RCA Microwave Tube Operations
F. Sterzer - RCA Microwave Tube Operations
F. Vaccaro - RCA Microwave Tube Operations
R. Gold - RCA Semiconductor and Materials
Hon C. Lee - RCA Semiconductor and Materials
C. J. Gurwacz - RCA Electron Tube Division
R. H. Siemens - RCA Electron Tube Division
John Donoho - RCA Shrewsbury, New Jersey

In addition to a general discussion of the progress under the contract, the possibility of additional modulator development directed toward meeting future radiosonde requirements was discussed. It was decided that RCA should propose such a program to be considered for addition to the contract.

January 24, 1963 - General Discussion and Review of Contract at RCA Laboratories, Princeton, New Jersey.

Present: Ivan L. Chase - U.S.A.E.R.D.L.

G. Hambleton - U.S.A.E.R.D.L.

E. McCormick - U.S.A.E.R.D.L.

D. Nelson - RCA Microwave Tube Operations

F. Sterzer - RCA Microwave Tube Operations

F. Vaccaro - RCA Microwave Tube Operations

C. J. Gurwacz - RCA Electron Tube Division

R. H. Siemens - RCA Electron Tube Division

The breadboard oscillator unit (Item 3a under the Contract) was demonstrated and delivered to Mr. Hambleton. The discussion covered general progress under the contract as well as battery requirements, modulation considerations and environmental requirements. It was agreed that RCA will make AM modulation tests using the RCA transistor modulator and that the breadboard unit will be tested with a Signal Corps modulator at the Signal Corps Laboratories.

May 10, 1963 - General Discussion and Review of Contract at RCA Laboratories, Princeton, New Jersey.

Present: Ivan L. Chase - U.S.A.E.R.D.L.

E. McCormick - U.S.A.E.R.D.L.

D. Nelson - RCA Microwave Tube Operations

F. Sterzer - RCA Microwave Tube Operations

R. Gold - RCA Semiconductor and Materials

E. T. Casterline - RCA Semiconductors and Materials

The general progress under the contract was discussed. Preliminary results on acceleration tests were reported and plans for further environmental tests discussed. The new tunable oscillator circuit was described as well as a cylindrical rolled up version designed for low cost. It was agreed that the prototype oscillators to be delivered in July will be of the standard flat box type rather than the cylindrical.

June 17, 1963 - General Discussion and Review of Contract at RCA Laboratories, Princeton, New Jersey.

Present: Ivan L. Chase - U.S.A.E.R.D.L.

George Hambleton - U.S.A.E.R.D.L.

John Brown - Ballistic Research Laboratories, Aberdeen Proving Grounds

W. J. Cruickshank - Ballistic Research Laboratories, Aberdeen Proving Grounds

D. Nelson - RCA Microwave Tube Operations

F. Sterzer - RCA Microwave Tube Operations

R. Gold - RCA Semiconductor and Materials

The general progress under the contract was discussed. Parts for the cylindrical rolled up version of the oscillator were shown. RCA agreed to make one of the three prototype oscillators in the cylindrical version. The requirements for a tunnel-diode oscillator for gun probe radiosondes were discussed.

August 2, 1963 - Discussion of Tunnel-Diode Oscillators for Gun Probe Radiosonde at RCA Laboratories, Princeton, New Jersey.

Present: George Hambleton - U.S.A.E.R.D.L.

E. McCormick - U.S.A.E.R.D.L.

V. Gelnovatch - U.S.A.E.R.D.L.

W. Cruickshank - Ballistic Research Laboratories, Aberdeen Proving Grounds

C. Shafer - Ballistic Research Laboratories, Aberdeen Proving Grounds

A. Blicher - RCA Semiconductor and Materials

E. Casterline - RCA Semiconductor and Materials

R. Gold - RCA Semiconductor and Materials

D. Nelson - RCA Microwave Tube Operations

F. Sterzer - RCA Microwave Tube Operations

Further discussion of requirements and specifications for tunnel-diode oscillators suitable for gun probe radiosondes was held. It was agreed that RCA will inform USASRDL as to what additional phases of effort would be required in order to include development of oscillators for gun probes in the present program.

September 6, 1963 - Review of Contract and discussion of the possible use of tunnel diode oscillator in Republic Aviation Radiosondes at RCA Laboratories, Princeton, New Jersey.

Present: Ivan Chase - U.S.A.E.R.D.L.

E. McCormick - U.S.A.E.R.D.L.

P. Berger - Republic Aviation

L. DeBacker - RCA Microwave Tube Operations

F. Sterzer - RCA Microwave Tube Operations

D. Nelson - RCA Microwave Tube Operations

R. Gold - RCA Semiconductor and Materials Division

The general progress under the contract was discussed. The specifications required by Republic Aviation were reviewed. It was agreed that RCA would furnish Republic Aviation guidance price quotations on tunnel diode oscillators.

February 25, 1964 - Review of Contract and discussion of a contract extension at RCA Laboratories, Princeton, New Jersey.

Present: Ivan Chase - U.S.A.E. R.D.L.

M. McCormick - U.S.A.E.R.D.L.

R. Siemens - RCA Microwave Tube Operations

F. Sterzer - RCA Microwave Tube Operations

D. Nelson - RCA Microwave Tube Operations

R. Gold - RCA Semiconductor and Materials Division

E. Casterline - RCA Semiconductor and Materials Division

The general progress under the contract was discussed. A proposed contract extension which would include delivery of additional fixed frequency tunnel diode oscillators suitable for high acceleration applications was discussed.

April 10, 1964 - Review of Contract and general discussion of tunnel diode applications at RCA Laboratories, Princeton, New Jersey.

Present: W. Matthei - U.S.A.E.R.D.L.

A. Blicher - RCA Semiconductor and Materials Division

R. Gold - RCA Semiconductor and Materials Division

R. Siemens - RCA Microwave Tube Operations

F. Sterzer - RCA Microwave Tube Operations

E. Diamond - RCA Microwave Tube Operations

D. Nelson - RCA Microwave Tube Operations

The general progress under the contract was discussed. The status of tunnel diodes and other solid state devices for microwave applications was reviewed.

May 13, 1964 - Review of Contract at RCA Laboratories, Princeton, New Jersey.

Present: Ivan Chase - U.S.A.E.L.

M. McCormick - U.S.A.E.L.

E. Casterline - RCA Semiconductor and Materials Division

E. Diamond - RCA Microwave Tube Operations

D. Nelson - RCA Microwave Tube Operations

The general progress on the contract was reviewed.

June 9, 1964 - Review of Contract at U.S.A.E.L., Fort Monmouth, New Jersey.

Present: W. Matthei - U.S.A.E.L.

I. Chase - U.S.A.E.L.

M. McCormick - U.S.A.E.L.

L. DeBacker - RCA Microwave Tube Operations

M. Nowogrodzki - RCA Microwave Tube Operations

R. Siemens - RCA Microwave Tube Operations

F. Sterzer - RCA Microwave Tube Operations

D. Nelson - RCA Microwave Tube Operations

Progress on the contract was reviewed. Transistor-Oscillator-Multipliers were considered as a substitute for tunnel-diode oscillators.

August 14, 1964 - Review of Contract at U.S.A.E.L., Fort Monmouth, New Jersey.

Present: W. Matthei - U.S.A.E.L.

I. Chase - U.S.A.E.L.

M. McCormick - U.S.A.E.L.

E. Diamond - RCA Microwave Tube Operations

F. Sterzer - RCA Microwave Tube Operations

D. Nelson - RCA Microwave Tube Operations

Progress on the contract was reviewed. The desirability of substituting a transistor-oscillator-multiplier for the tunnel-diode oscillator was discussed.

November 6, 1964 - Review of Contract at RCA Laboratories, Princeton, New Jersey.

Present: I. Chase - U.S.A.E.L.

M. McCormick - U.S.A.E.L.

E. Diamond - RCA Microwave Tube Operations

C. Sun - RCA Microwave Tube Operations

F. Sterzer - RCA Microwave Tube Operations

D. Nelson - RCA Microwave Tube Operations

Progress on the contract was reviewed. Transistor-Oscillator-Multipliers were demonstrated.

SECTION IV

FACTUAL DATA

A. INTRODUCTION AND CHRONOLOGY.

The original objective of this contract was the development of a tunable tunnel diode oscillator giving 25 milliwatts power output in the frequency range 1660 to 1700 megacycles. The oscillator was to be designed for minimum production cost and to be adaptable for radiosonde applications. Included in the requirements were frequency variations of less than ± 2 Mc for ± 10% voltage changes and of less than ± 2 Mc for ambient temperature variations from -55° C to +75° C. It was also required that the oscillator be modulated, either AM or FM, by means of a blocking oscillator.

In March of 1964 an additional task was added to the contract. In order to meet a requirement of the Ballistic Research Laboratories of the Aberdeen Proving Ground the development of Ruggedized Tunnel Diodes including delivery of prototype models was added. Specifications called for a power output of 25 mw, a capability for frequency modulation and the requirement that the units withstand a 50,000 G acceleration. Shortly thereafter tests at the Ballistic Research Laboratories indicated that 25 milliwatts was insufficient power output for the system proposed and that several hundred milliwatts would be required. Since it did not appear that such power could be obtained from tunnel-diode oscillators during the period of the contract, RCA proposed that a transistor-oscillator-multiplier be substituted in the BRL requirement. This proposal was accepted and the BRL requirement was modified in May 1964 to call for the development and delivery of prototype models of Solid State Oscillators using the new RCA overlay transistor developed on contract DA-36-039-SC-90797.

By November, 1964, tunnel-diode oscillators for the standard radiosonde application had given power outputs of 25 mw and greater. Through the use of a simple transistor voltage regulator circuit the requirement that a frequency change of less than ± 2 Mc result from a ± 10% supply voltage change had been satisfied. A blocking oscillator circuit capable of providing the required frequency modulation had been satisfactorily tested. However, in order to attain 25 mw of output power, tunnel diodes having peak currents of 600 ma were required. Very low impedance circuits were necessary for oscillators using these high current diodes. Such circuits have low Q factors and as a result large frequency changes occurred with variation of ambient temperature. In order to reduce these changes to the ± 2 Mcs specified for temperatures of -55° C to +75° C, it appeared that complicated and expensive compensating circuitry would be required.

At this time preliminary results on the Solid State Oscillators for the BRL applications indicated that 250 mw of power output could be obtained using a low cost version of the overlay transistor operating simultaneously as an oscillator and as a frequency multiplier. Since this offered both the advantage of higher power output and greater ease of temperature compensation, RCA proposed the substitution of this type unit for the three remaining developmental model tunnel-diode oscillators on the standard radiosonde portion of the contract. (At this time the breadboard tunnel-diode oscillator, the three prototype tunnel-diode oscillators and three of the six required developmental model tunnel-diode oscillators had been delivered.) In November, 1964, this was approved and the contract modified to call for the substitution of three Solid State Harmonic Generators for the three remaining developmental model tunnel-diode oscillators to be delivered.

In the following sections the development of high current tunnel diodes capable of 25 mw power output at 1700 Mcs is discussed in Section IV B-1 and the oscillator circuits and results are described in Section IV B-2. In Section C, transistor-oscillator-multipliers for both the standard radiosonde and the BRL high acceleration application are described.

B. TUNNEL DIODE OSCILLATORS.

1. Tunnel Diodes

(a) Design Considerations

The design of a tunnel diode for use in a microwave oscillator circuit requires a consideration of the required power, the operating frequency, and the diode package configuration insofar as it affects circuit performance. These factors are discussed in this section.

Device Design - The maximum available power of a tunnel diode oscillator, Pa is given approximately by

$$Pa = 3/16\,(I_p - I_v)(V_v - V_p) \qquad (1)$$

where I_p and I_v are the currents and V_p and V_v are the voltages at the peak and valley points, respectively. Because of its greater voltage swing and higher peak-to-valley current ratio, gallium arsenide is better suited than germanium for high power microwave oscillators.

In order to approach the maximum available power at microwave frequencies, two conditions must be satisfied. The diode cutoff frequency, f_r, must be much greater than the frequency of oscillation, and the inductance associated with the diode package must be very small. The diode package design is discussed in the next section. The first condition, on cutoff frequency, directly affects the requirements on diode electrical parameters.

Analysis of the diode small signal equivalent circuit shown in Fig. 1 shows that the maximum frequency of oscillation (i.e., f_r) is given by

$$f_r = \frac{1}{2\pi RC}\sqrt{\frac{R}{r_s} - 1} \qquad (2)$$

where R is the minimum value of the magnitude of the diode negative resistance, C is the junction capacitance, and r_s is the diode series resistance. Since R is inversely proportional to peak current, equation 2 can be rewritten as

$$f_r = \left(\frac{1}{2\pi V_k}\right)\left(\frac{I_p}{C}\right)\left[\left(\frac{V_k}{I_p r_s}\right) - 1\right]^{1/2} \qquad (3)$$

where V_k, the proportionality constant, is 220 millivolts for gallium arsenide.

The required parameters can be obtained from equations 1 and 3. The value of (V_v-V_p) for gallium arsenide is about 0.4 volts. Recognizing that the maximum available power will not be delivered to the load, because of diode and circuit losses, to obtain 25 milliwatts we may set Pa = 40 milliwatts in equation 1. This gives (I_p-I_v) = 535 milliamperes. Since $I_p/I_v \geq 15$, this gives $I_p \doteq 570$ ma. Because of the approximations involved in analysis, it is reasonable to round off this figure, and set I_p = 600 ma ± 10%.

It is obvious, from examination of equation 3, that a high cutoff frequency requires a high ratio of (I_p/C) and a small series resistance. Since both I_p and C are directly proportional to junction area (assuming a uniform tunnel current density), (I_p/C) is independent of junction area. Furthermore, I_p can be expressed in terms of the junction depletion layer width, W, by

$$I_p = \frac{k_1 e^{-k_2 W}}{W} \qquad (4)$$

where k_1 and k_2 are constants. Since $C \propto \frac{1}{W}$ and $W \propto \frac{1}{N_r^{1/2}}$, this can be rewritten as

$$(I_p/C) = k_3\, e^{-k_4/N_r^{1/2}} \qquad (5)$$

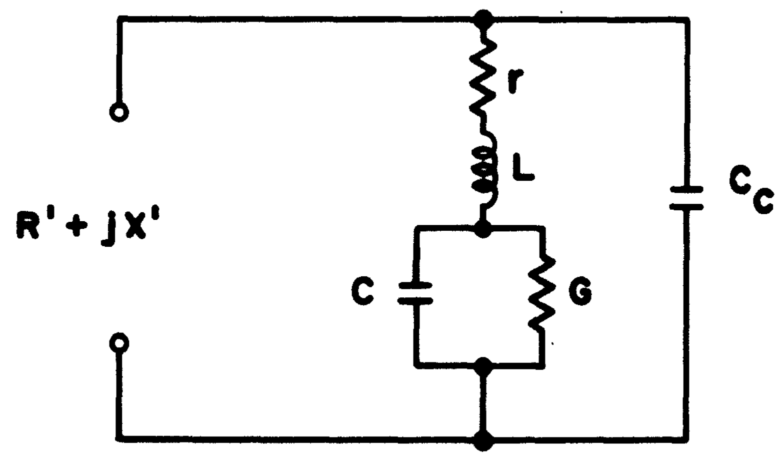


FIG.1 EQUIVALENT CIRCUIT OF TUNNEL DIODE

where k_3 and k_4 are constants, and N_r, the reduced doping level, is given by

$$N_r = \frac{N_a - N_d}{N_a - N_d} \qquad (6)$$

Here, N_a and N_d are the ionized acceptor and donor impurity concentration, respectively. Equation 5 shows that a high value of I_p/C requires a high impurity concentration. N_d is determined by the alloying cycle used to form the p-n junction, and is optimized empirically. N_a is determined by the conditions under which the gallium arsenide crystal is grown. Values of N_a on the order of 8 to 9 x 10^{19} atoms/cm^3 were obtained. The corresponding I_p/C ratio ranged between 15 and 25 ma/pf.

In order to achieve high output power, the cutoff frequency should be at least three times the operating frequency. For $f = 1.7$ gc, we require that $f_r = 5$ gc. By using very thin semiconductor pellets (less than 2 mils) and small alloy dots (about 3 mils), diodes could be made with series resistance between 0.2 and 0.3 ohms. From equation 3, the corresponding values of f_r are between 6 and 12 gc.

In summary, the various design considerations discussed above led to a design specification for $I_p \approx 600$ ma, $I_p/C \approx 15$ to 25 ma/pf, and $r_s \leq 0.3$ ohms. Such diodes were made, with $f_r \approx 6$ to 12 gc.

Package Design - As the peak current of the tunnel diode is increased, the inductance of the diode becomes an increasingly important factor, not only from the standpoint of obtaining the desired operating frequency, but also due to the difficulty of loading the diode in order to obtain a substantial portion of the available power as output power. Consider a 200 ma gallium arsenide tunnel diode having an inductance of 250 ph. (Such diodes had been used for microwave oscillators at the start of this program.) At 1680 mc the reactance of this

inductance is about 2.5 ohms. If the diode parameters are such that the self-resonant frequency of the diode is near 1500 mc the equivalent circuit of an oscillator operating at 1500 mc consists essentially of the diode equivalent circuit shown in Fig. 1 and a load resistor connected across the terminals. The voltage swing of such an oscillator will be about 500 mv and the current swing about 100 ma. The voltage drop across the diode inductance will be 100 ma times 2.5 ohms or 0.25 volts. Since this voltage is in quadrature with the voltage across the resistive load

$$V^2 \text{ across inductance} + V^2 \text{ across load} = V^2 \text{ total swing}$$

$$(0.25)^2 + V^2 \text{ across load} = (0.5)^2$$

and V across load = 0.43 volts. Thus about 85% of the available voltage swing occurs across the load resistor and with proper choice of load resistor this percentage of available power may be obtained as output power. If, however, the peak current of the diode is increased to 400 ma with no reduction in inductance, the current swing becomes about 200 ma, the voltage swing remains about 500 mv and the voltage across the inductance increases to 500 mv. Thus, the voltage across the load resistance would be zero and therefore the current swing must be considerably less than that assumed and the output will be substantially below the available power. This loss in output power becomes worse for diodes with even higher peak currents (e.g., 600 ma). It can be alleviated only by reducing the inductance associated with the diode package.

(b) Developmental Work

Package Development - The first diodes produced under this contract were fabricated in the package shown in Fig. 2, and had peak currents in the 200 ma range. The measured average inductance of these units were 250 pH. Dummy packages containing a nickel base resembling the diode wafer, but otherwise similar

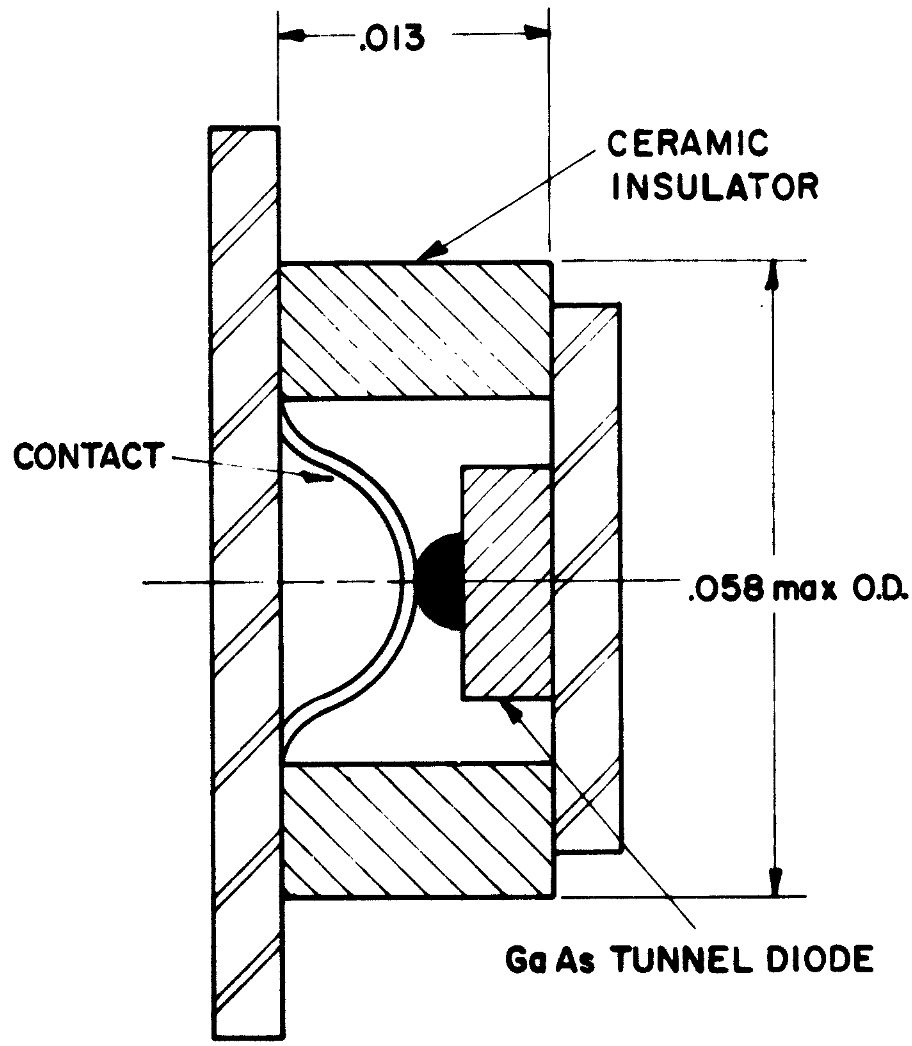


FIG.2 -TUNNEL DIODE PACKAGE

90773 F

in construction to the actual diodes, were also measured. The difference between the measured inductance and the inductance of the active diode was found to be insignificant. These inductance measurements indicated that a considerable portion of the lead inductance results from the conveyance of current from the strip transmission line to the tunnel diode terminating it.

The dimensions of the strip transmission line were established so that the strip line impedance level was on the order of (not necessarily equal to) the tunnel diode impedance level. The magnitude of the tunnel diode negative resistance, R, is given for gallium arsenide by

$$R \approx \frac{220}{I_p} \tag{7}$$

where R is in ohms and I_p in milliamperes. Thus, for I_p between 200-500 ma, R falls between 1 ohm and 0.4 ohm. For a comparable strip line impedance level, a thin dielectric must be used with moderately wide conducting strips. For the 200 ma diodes used initially, the transmission line used .010" Teflon, and a .0280" conducting strip. The tunnel diode terminating this line was .054" in diameter, with the actual junction diameter considerably smaller than this. It is apparent that the convergence of current from the wide strip to the small tunnel diode can result in a contribution to the effective inductance. To counteract this, a method of packaging the tunnel diode in such a way that, when connected into the strip transmission line the length of the line over which the discontinuity in size takes place is smaller than with the conventional package, was adopted. The configuration of this package is shown in Fig. 3. An eighth-inch diameter disc of strip transmission line O.D. = 0.125" I.D. = 0.030" is soldered to a quarter-inch diameter brass disc. The tin dot is alloyed to the gallium arsenide pellet, which is then soldered to small brass disc. A screen is used to connect the tin

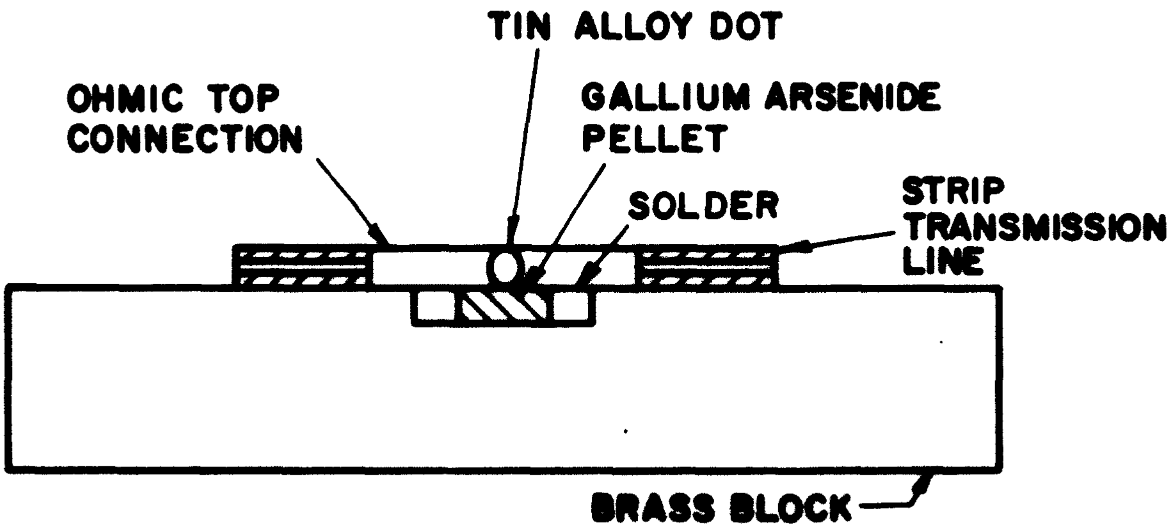


FIG.3 LOW INDUCTANCE TUNNEL DIODE PACKAGE

dot to the top conductor of the strip transmission line. The resultant structure can then be incorporated directly into a larger strip line circuit.

Initially, a problem was encountered with this configuration, resulting from the large thermal mass of the copper disc. The high temperature used in the mounting operation caused a softening of the Teflon dielectric in the strip line and ruined the diodes by causing decreases in the initial peak currents. This problem was solved by first, reducing the thickness of the Cu disc to 1/32" and thus reducing its thermal mass, and second, by gold plating the disc to improve solderability. The remainder of the diodes for this contract were supplied in this type of package. The dimensions of the disc were 1/4" x 1/32". The strip-line washer had an O.D. of 0.125" and an I.D. of 0.030". Inductance measurements on units mounted in this package indicated a substantial decrease in the diode inductance to a value of about 75 pH.

<u>Semiconductor Material Requirements</u> - It was pointed out in Part (a) that a high carrier concentration material would be needed to fabricate the desired units. At the beginning of this contract, some material having a carrier concentration in the 8-9 x 10^{19} atoms/cm^3 range had been grown but the process was not sufficiently well controlled to insure reproducibility. Most of the available material was in the 6.0 x 10^{19} atoms/cm^3 range. In an attempt to increase the impurity concentration to the desired level, doping by diffusion was investigated. A grown GaAs wafer was placed into an evacuated ampoule along with 40 mg of pure Zn. The ampoule was then placed into a furnace at 975°C for 18 hours and the Zn allowed to diffuse into the wafer. Initial results were poor, the surface of the crystal alloyed with Zn. Other combinations of time and temperature were tried but all results were unsatisfactory. Finally, improvements in crystal growing techniques at the RCA Semiconductor and Materials Division enabled

us to obtain a good supply of highly doped crystal. The process by which the crystal was grown is fairly reproducible and thus crystal supply was no longer a major problem.

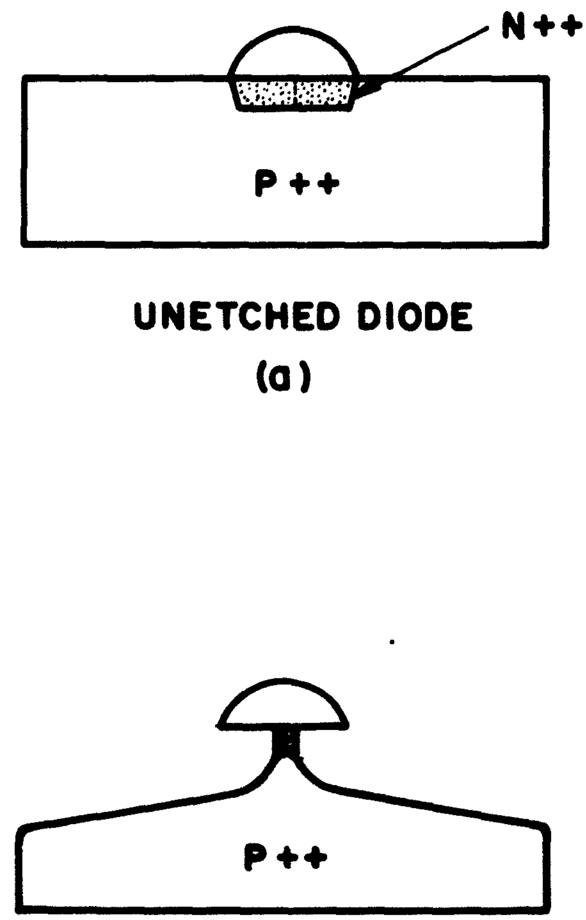
Diode Series Resistance - From equation 3, we can see the dependance of f_r on the diode series resistance. Many factors contribute to the total diode resistance, all of which must be minimized in the design of microwave tunnel diodes of the type being considered. The most significant contribution to the diode series resistance results from an electrolytic etching of the diode. Before etching, the tunnel diode junction is as shown in Fig. 4a. The resistance through the diode is a spreading resistance given approximately by

$$r_s = \frac{\rho}{2d} \qquad (8)$$

where ρ is the crystal resistivity and d the junction diameter. After etching the diode exhibits the structure shown in Fig. 4b. The series resistance now lies mainly in the stem and is given by the expression for the resistance of a cylinder

$$r_s = \frac{\rho \ell}{A} \qquad (9)$$

where ℓ is the length of the stem and A is the cross-sectional area. It has been shown that the length of this stem can be reduced by using the smallest alloy dots possible to form the tunneling junctions.[1] This is because large junction areas require more etching to obtain the desired junction area. Moreover, p-type material etches faster than n-type and therefore, much more of the p-type material is etched away. This causes the stem shown in Fig. 4b to form. The smaller the alloy dot, the less etch time is required and hence, the shorter the stem.[1] One may also note from equations 6 and 7 that r_s is dependent on the crystal resistivity.



UNETCHED DIODE
(a)

ELECTROLYTICALLY
ETCHED DIODE
(b)

FIG. 4

Since resistivity is inversely proportional to impurity concentration, and high concentrations are used to obtain high I_p/C ratios, the lowest available resistivity material is being used.

The length of the resistance path through the bulk of the material should also be reduced to a minimum. A few different methods were tried, such as etching a hole in the GaAs pellet on the opposite side of the junction and then alloying a metal into it as shown in Fig. 5. Because the resistance of the metal is less than that of the semiconductor, the resistance through the unit should be less. However, this method failed to produce any noticeable difference in series resistance.

Another approach was to metallize the top surface of the pellet very close to the contact dot so that the distance from the contact dot to the metal layer is less than the thickness of the pellet, as shown in Fig. 6. Results were poor due to peeling of the metal film and difficulty in making good ohmic contact to the surface. Good contact could most likely have been achieved, but there is doubt that there was any distinct advantage to this geometry because the skin depth at 2 kmc is 10 mils, while typical pellets at this point were about 2 mils thick.

An experiment was conducted in which a GaAs wafer having a carrier concentration of 9×10^{19} atoms/cc was divided in two. One-half was lapped to a thickness of 2 mils while the other half was lapped to 1 mil. Both halves were diced into 0.020" x 0.020" pellets and diodes were fabricated from both using exactly the same conditions. The results are shown in Table 1. The units fabricated from the 1 mil thick pellets seem to have a slightly lower average value of series resistance and capacitance. Further tests of the same kind showed this

TABLE I

Comparison of Series Resistance for 1 and 2 Mil Pellet Thickness

1 Mil Pellet						2 Mil Pellet					
No.	I_p(ma)	I_v(ma)	R_s	C_v(pf)	f_{co}(kmc)	No.	I_p(ma)	I_v(ma)	R_s	C_v(pf)	f_{co}(kmc)
1	580	55	.245	48.0	6.48	1	590	50	.37	26.5	-
2	600	40	.22	51.0	8.1	2	600	40	.27	59.5	3.90
3	590	50	.27	42.5	6.4	3	580	45	.32	33.0	5.55
4	600	35	.32	33.0	4.95	4	580	40	.32	29.0	6.26
5	600	35	.37	27.0	-	5	600	35	.27	40.0	6.43
6	600	40	.32	24.5	6.6	6	600	45	.245	55.0	5.53
Avg.			.290	37.6		Avg.			.299	40.8	

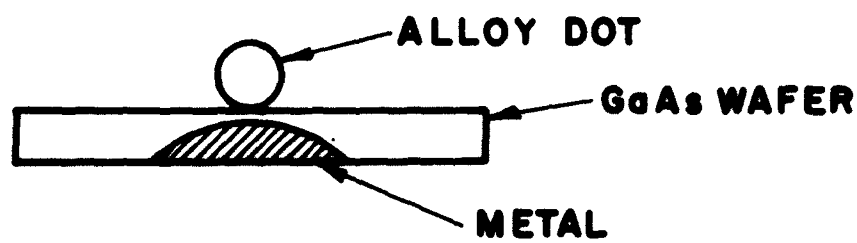
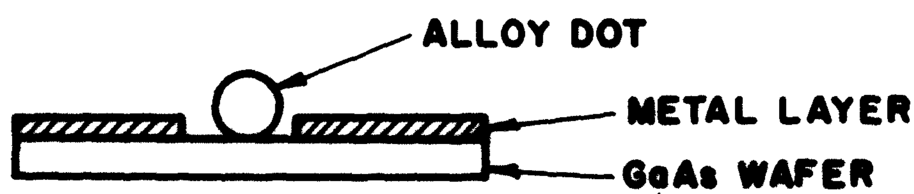


FIG. 5



EXPERIMENTAL DIODES

FIG. 6

to be the case in most instances. Because of these results, all diodes were subsequently fabricated with pellets having a thickness of 1.0 - 1.5 mils. One disadvantage of this technique is an increased difficulty in handling the very thin pellets. In addition, there is a difference in thermal expansion coefficients between GaAs and the evaporated, sintered metal layer used for the back contact. This causes the GaAs wafer to warp. One might expect crystalline strains to be introduced by warping, thus seriously affecting the tunnel diode characteristics. However, this has not been observed.

Diode Cutoff Frequency versus Impurity Concentration and Peak Current Level - The alloying process in tunnel diode fabrication always results in a junction area and peak current level which is considerably higher than that usually desired. The junction area is reduced by electrolytic etching to produce the required value of I_p. The effect of etching on diode cutoff frequency can be seen by examination of equation 3. As has already been stated, I_p/C is independent of area, provided that the current density is uniform across the junction area. For the case where series resistance is primarily due to spreading effects, r_s will increase inversely with the square root of junction area, whereas I_p decreases directly with area. Thus, as I_p is decreased by etching, the product $I_p\ r_s$ decreases. Equation 3 predicts, for this case, an increase in f_r as the diode is etched to lower peak currents. However, as discussed in Section (c), the long stem produced by prolonged etching causes the series resistance to become inversely proportional to the junction area, rather than its square root. Thus, the $I_p\ r_s$ product and f_r should become constant with prolonged etching. One would attribute deviations from this behavior in f_r to a non-uniform current distribution. Actually, one does not expect I_p/C to be constant. This is because the tunnel current density is an exponential function of doping level, whereas junction

capacitance is only a square root function of doping. Since the doping impurities will not be distributed perfectly uniformly across the junction area, random variations in I_p/C are expected.

To investigate this, four groups of diodes were fabricated from p-type GaAs having carrier concentrations of 4.2×10^{19}, 6.5×10^{19}, 8.0×10^{19} and 9.5×10^{19} carriers/cc. Each group was prepared under the same conditions of alloying temperature, time, and alloy dot size. The units were then etched electrolytically and their electrical parameters measured at various points. Care was taken to insure that the diodes were not electrically degraded during etching. Figures 7, 8, and 9 show the variation in I_p/C with etching. If the current density was absolutely uniform across the entire junction area, these curves would be horizontal straight lines. In other words, these curves are a measure of the non-uniformity of the current density across the junction. The decrease in I_p/C at very low peak currents are not understood. It cannot be attributed to strains induced by etching to small junction areas, since the strain would also produce a large increase in valley current. Such change has not been observed. Another possible explanation is that, during alloying the interior of the alloy dot remains at a high temperature for a slightly longer time than the outside surface of the dot. This would explain a decrease in I_p/C as the outer portion of the junction is etched away. An experiment was performed to test this hypothesis. Several diodes were made with very large (about 0.008" diameter) alloy dots, to enhance the effect of non-uniform temperature during alloying. Unfortunately, the results were inconclusive.

The variation in cutoff frequency with etching is shown in Figs. 10 through 13. It is seen that f_r at first increases as I_p is reduced. A maximum is reached, beyond which further etching causes f_r to decrease again. The latter

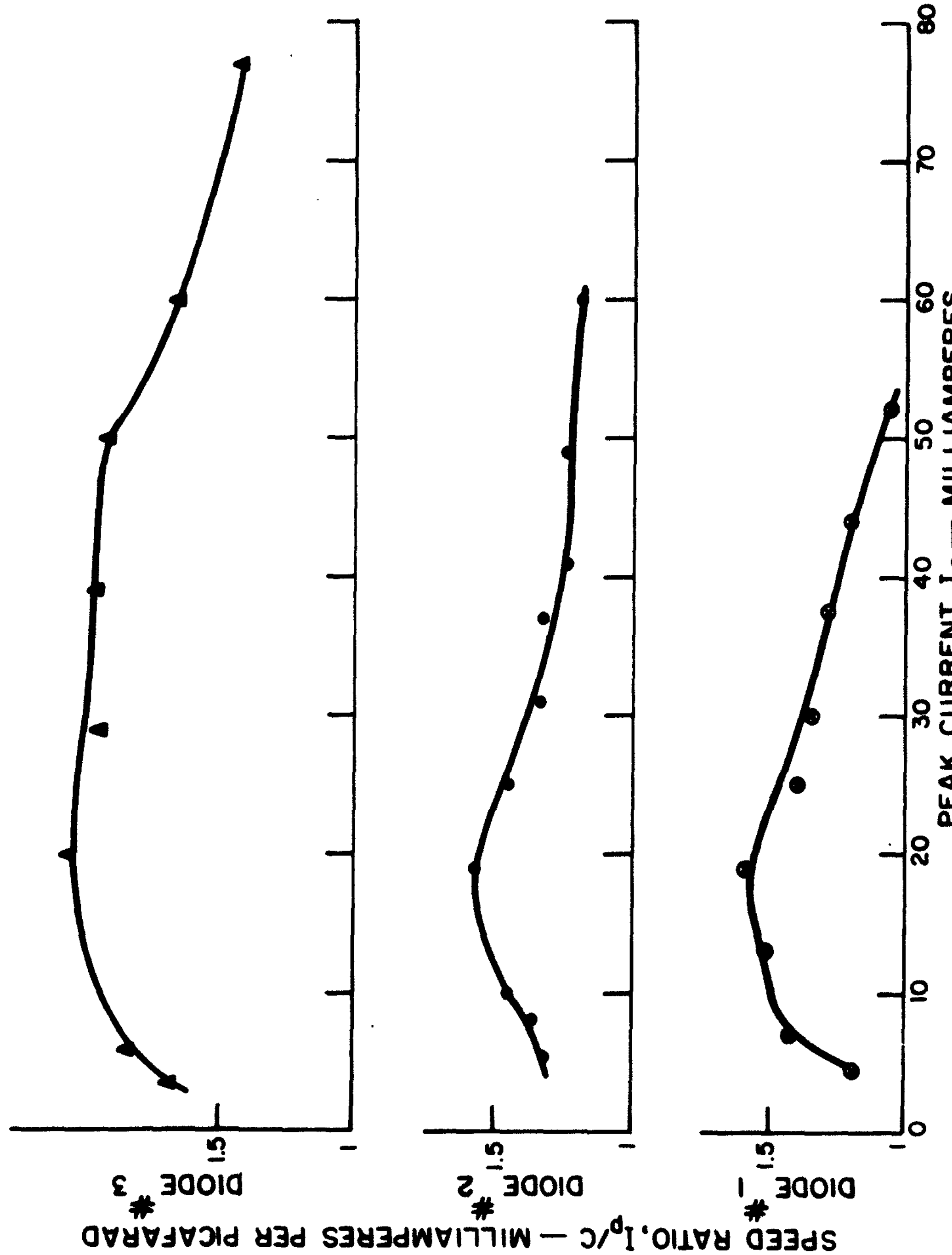


FIG. 7 SPEED RATIO vs. PEAK CURRENT. $N = 4.2 \times 10^{19}$

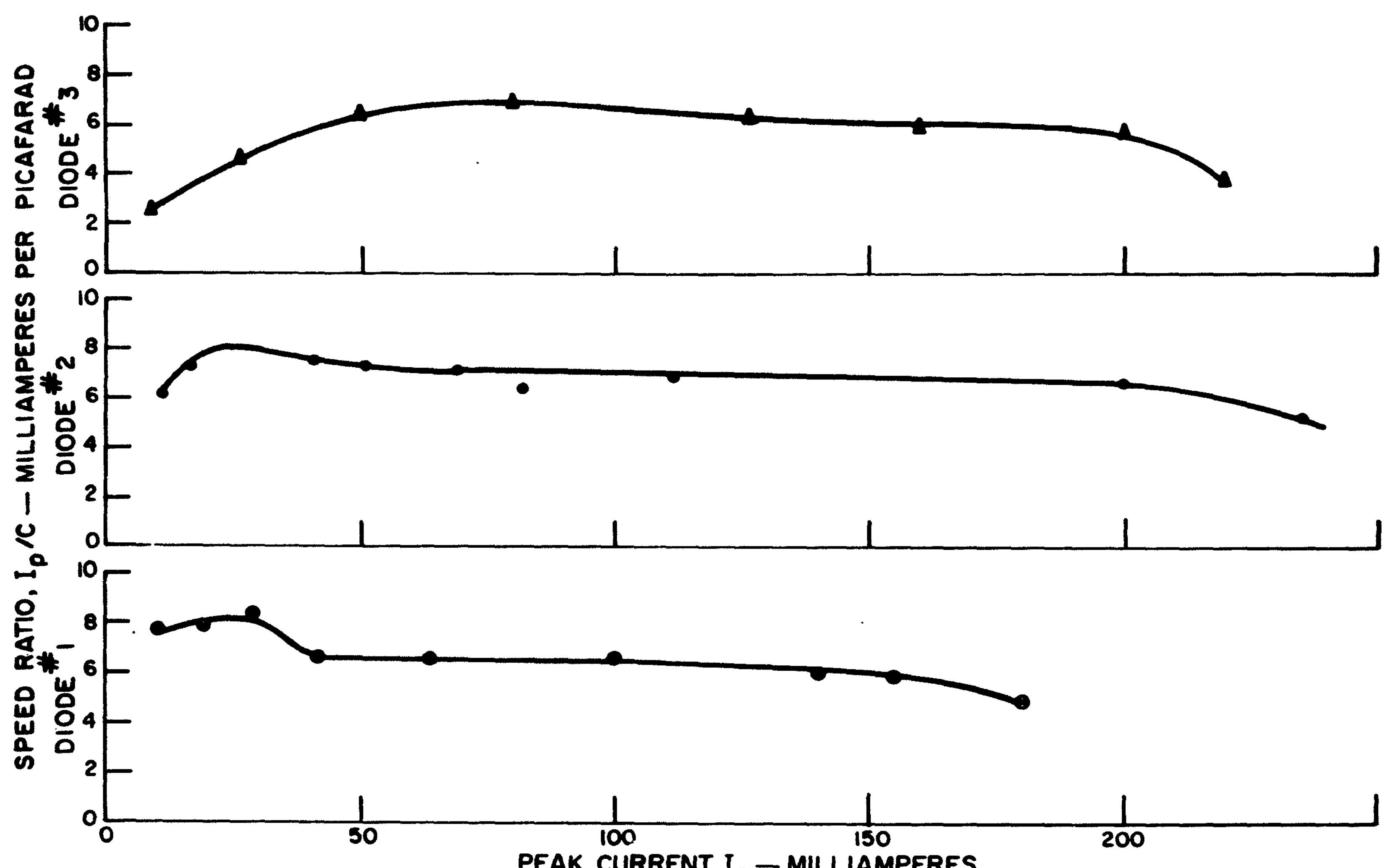


FIG. 8 SPEED RATIO vs. PEAK CURRENT. N= 6.5×10^{19}

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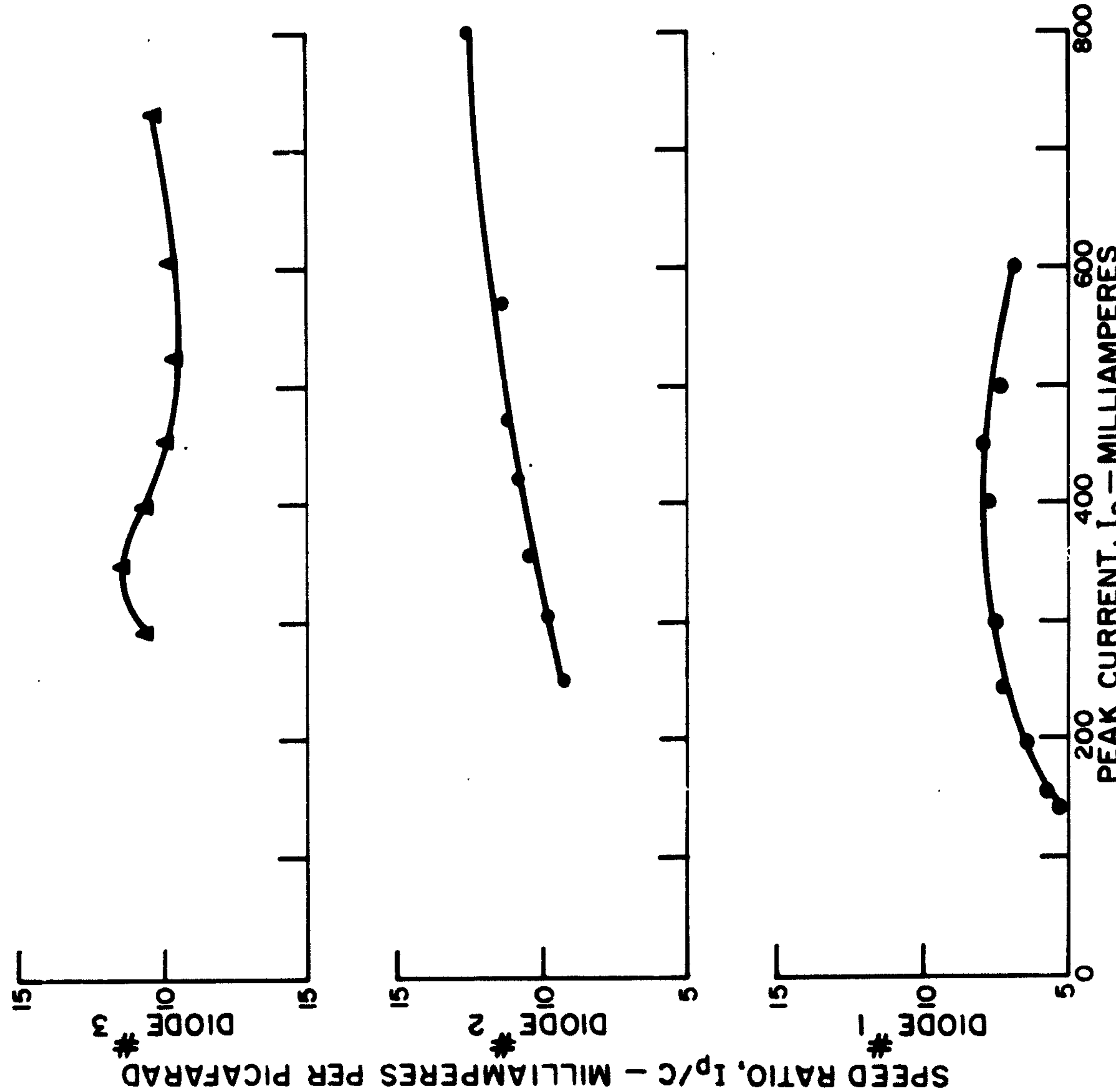

FIG. 9 SPEED RATIO vs. PEAK CURRENT. $N=9.5\times10^{19}$

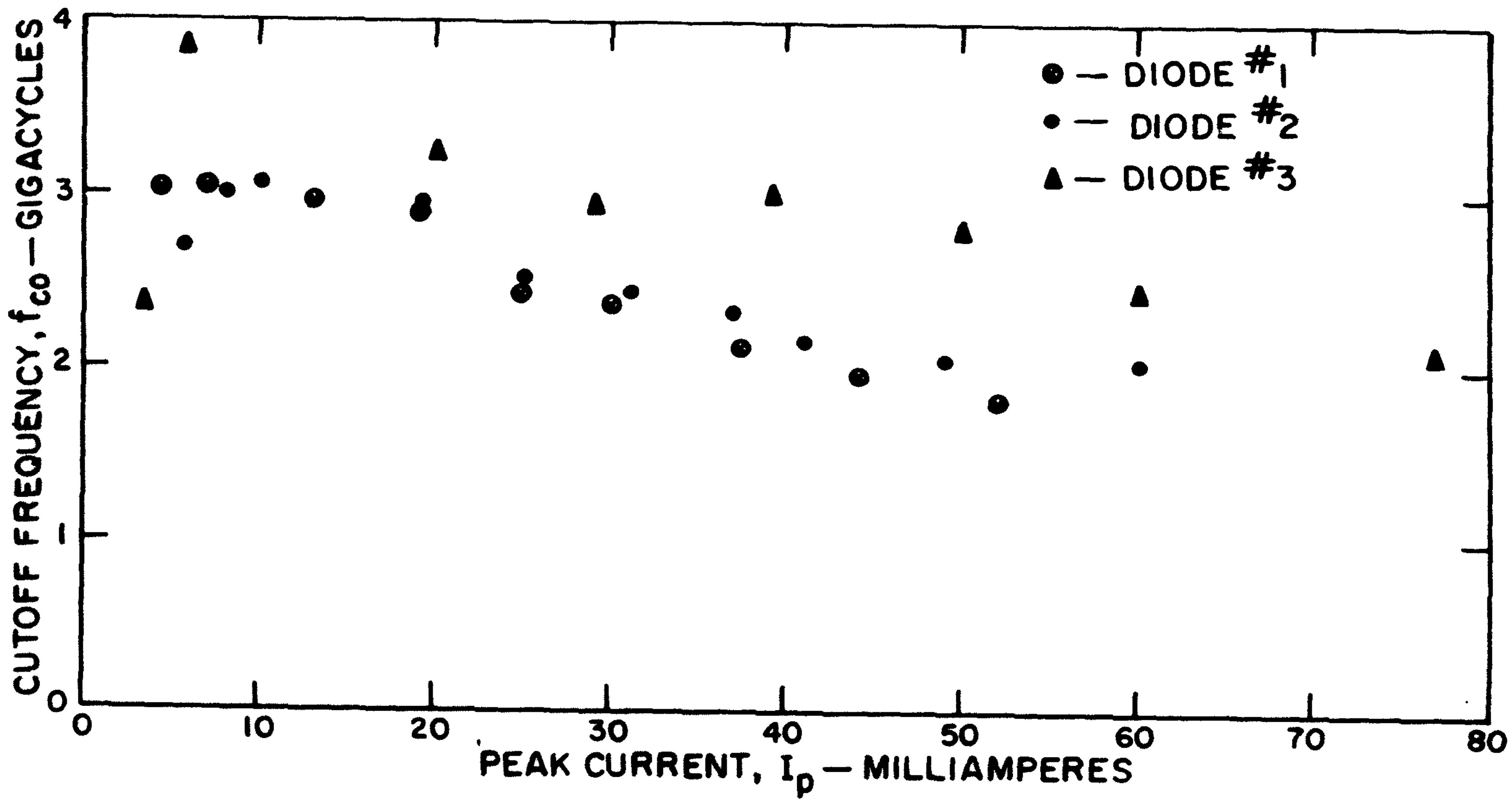

FIG. 10 CUTOFF FREQUENCY vs. PEAK CURRENT FOR GALLIUM-ARSENIDE TUNNEL DIODES. MATERIAL CARRIER CONCENTRATION 4.2×10^{19} ATOMS PER CUBIC CENTIMETER

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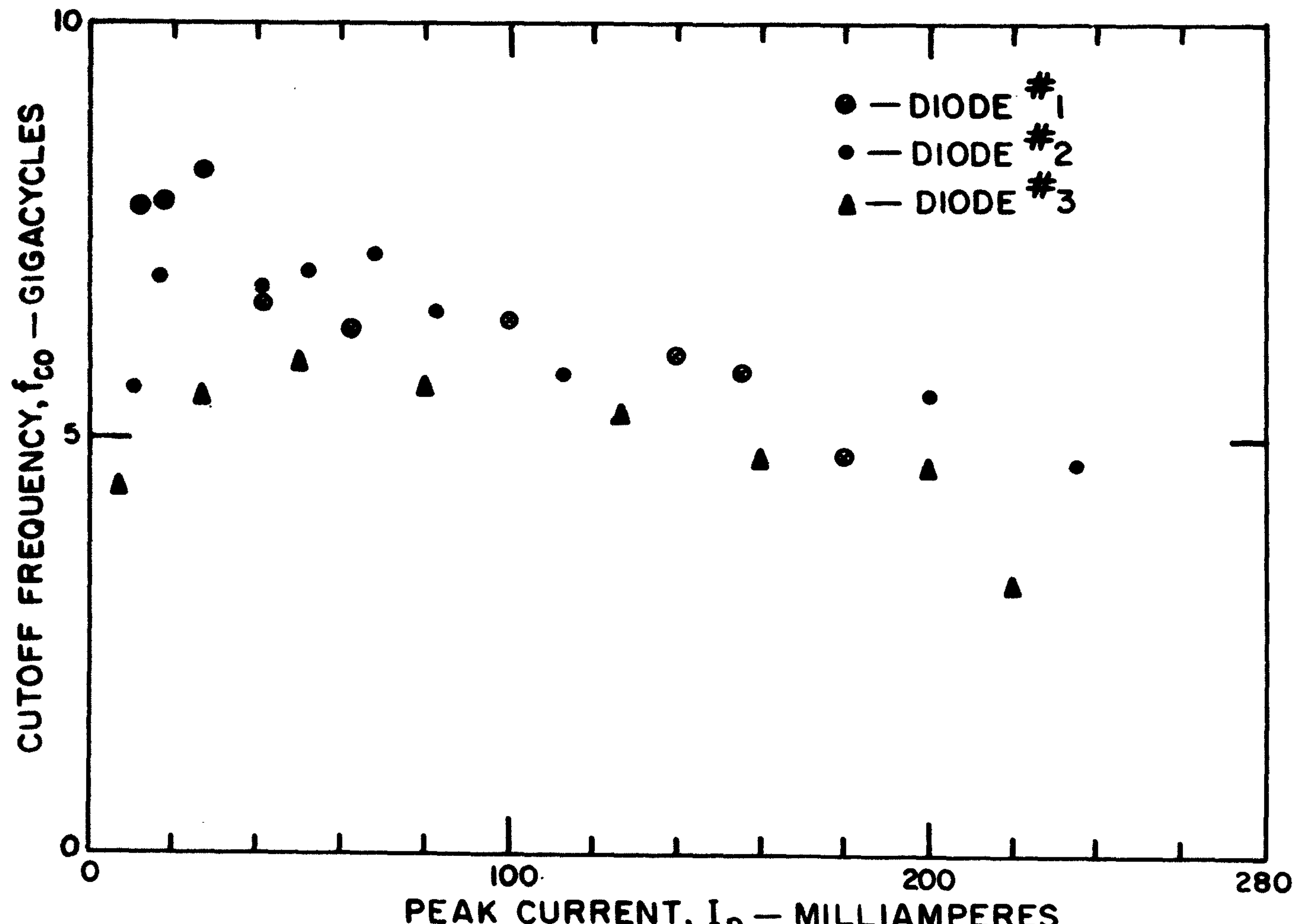

FIG. 11 CUTOFF FREQUENCY vs. PEAK CURRENT FOR GALLIUM-ARSENIDE TUNNEL DIODES. MATERIAL CARRIER CONCENTRATION 6.5×10^{19} ATOMS PER CUBIC CENTIMETER

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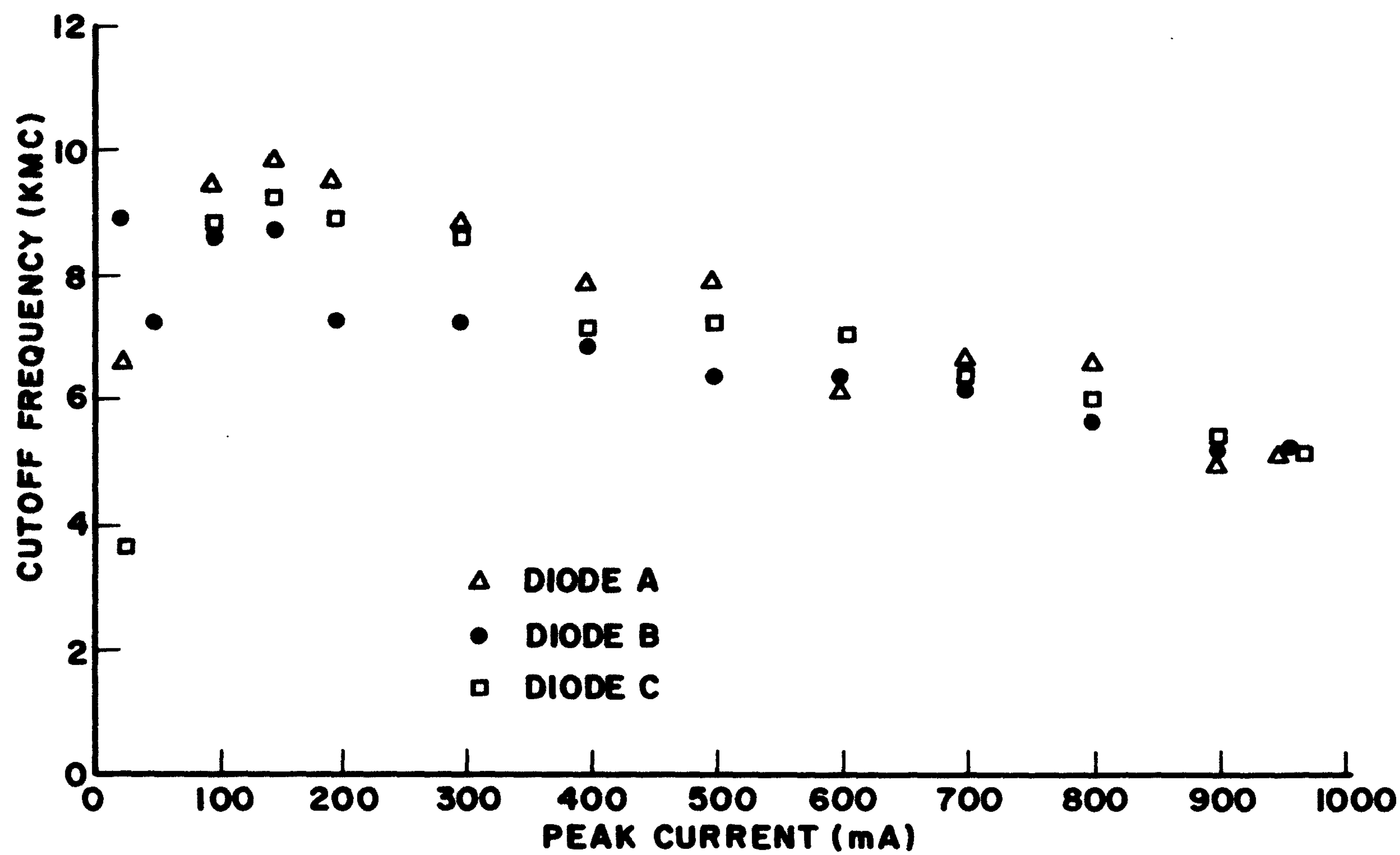

FIG. 12 CUTOFF FREQUENCY vs PEAK CURRENT
CARRIER CONC. 8.0×10^{19} ATOMS/CC

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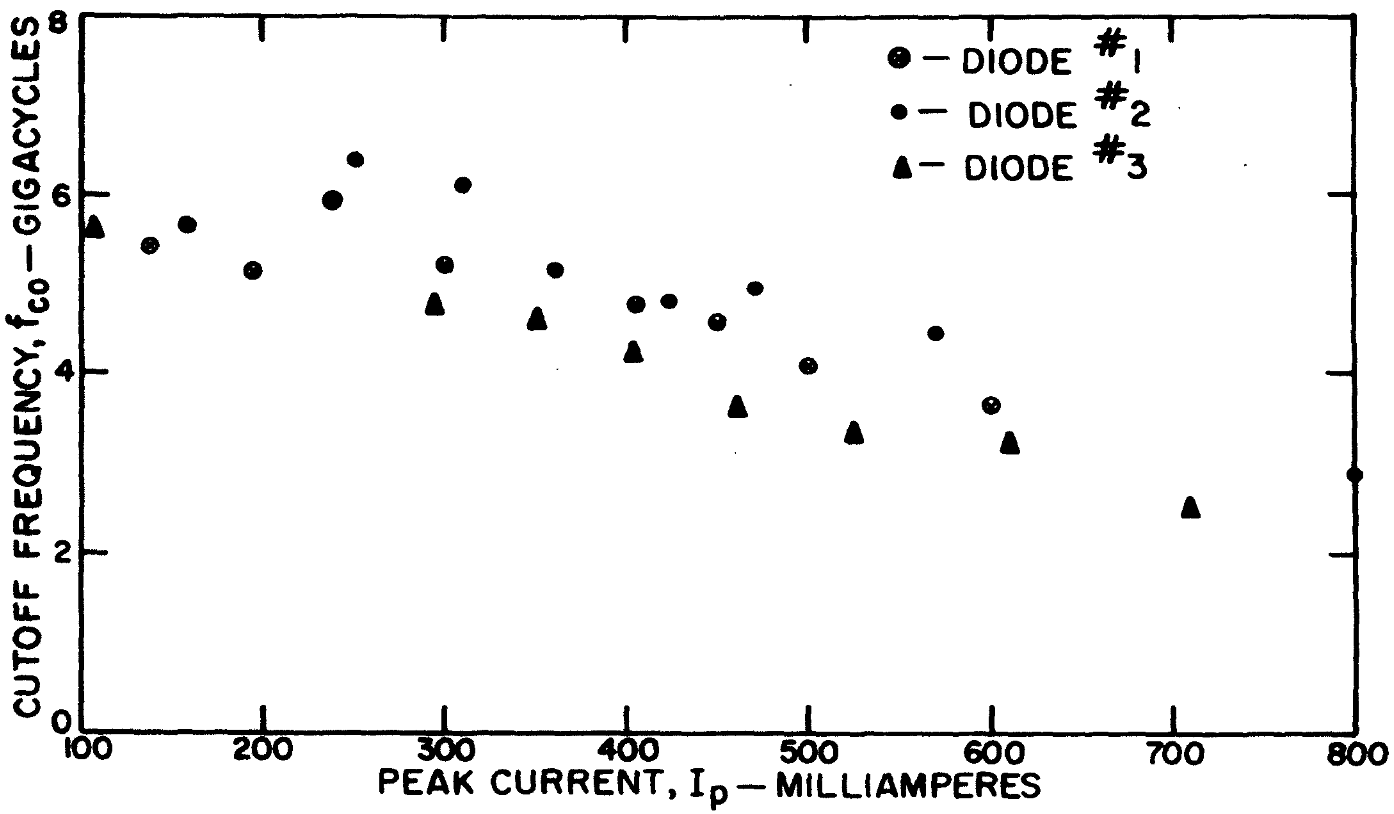

FIG.13 CUTOFF FREQUENCY vs. PEAK CURRENT FOR GALLIUM-ARSENIDE TUNNEL DIODES. MATERIAL CARRIER CONCENTRATION 9.5×10^{19} ATOMS PER CUBIC CENTIMETER

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decrease is attributed to the decrease in I_p/C. The initial increase in f_r is taken as evidence that the explanation given above is correct. It can be seen that the maximum in f_r occurs at higher values of I_p for high concentration material. This is because the higher concentration pellets etch more rapidly, thus causing the formation of the long stem (Fig. 4b) at higher peak currents. It should be noted that the diodes with carrier concentration of 9.5×10^{19} atoms/cc opened (i.e., the alloy dot lifted from the pellet before a clearly defined maximum could be reached). This is understandable because the high current density corresponding to such a high doping density results in junctions having a very small area and consequently are very fragile. Attempts were made to shift this maximum value of f_{co} as close to 600 ma as possible through proper choice of material and alloying cycle. It was found that this maximum does not occur at peak currents greater than 200 ma.

Distributed Junctions - By using the most highly doped crystal available, by reducing the length of the resistance path to a practical minimum (1 mil) and by using a very small alloy dot, the diode series resistance was considerably reduced. The low inductance strip line package described earlier reduced the inductance to about 75pH. Further reductions in series resistance and inductance might be accomplished by using a distributed (e.g., a line or ring) junction, which would both increase the aspect ratio of the junction and reduce the necking brought about by etching.

One approach was the ring-type junction shown in Fig. 14. In this approach a 2 mil diameter SiO dot is vacuum deposited on a GaAs wafer. The dot is then covered with a thin metal film as shown in Fig. 14a.. The SiO layer is made thick enough so as not to add to the unit capacitance. A tin dot is then alloyed over the SiO inert layer, the object being to form a junction around the outer edge

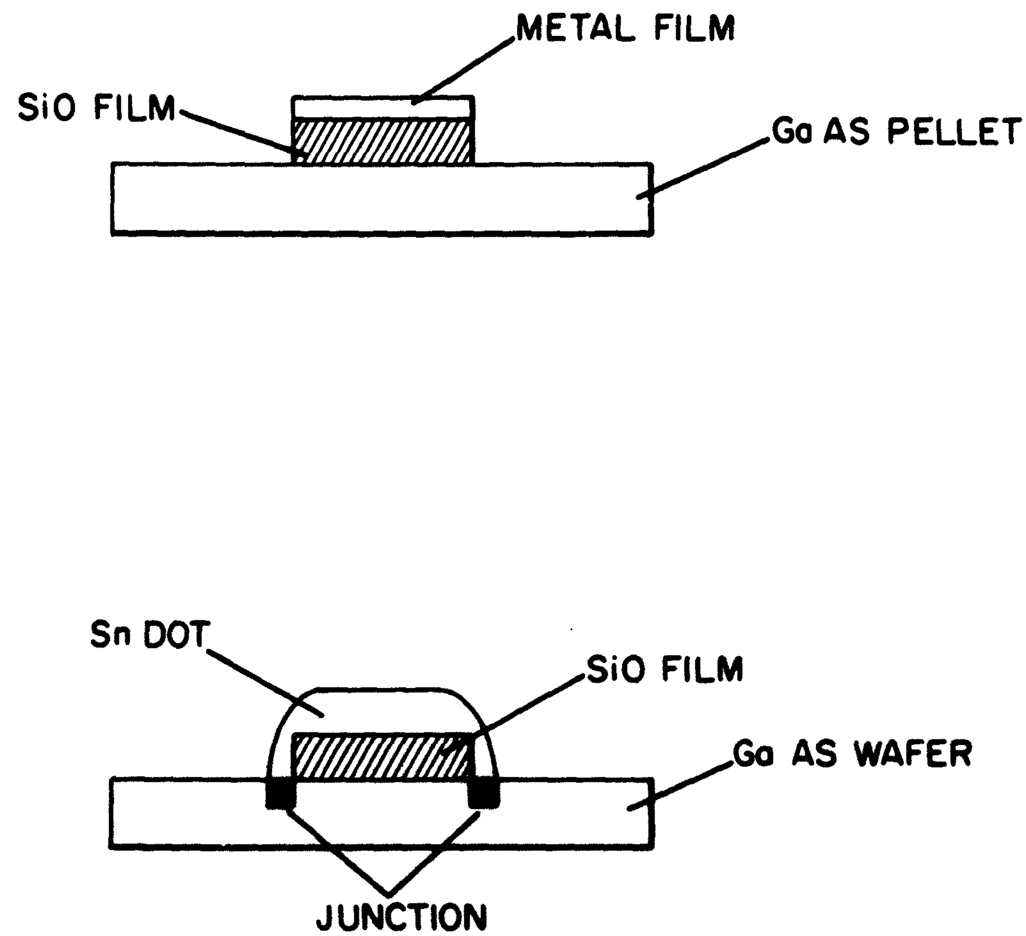

FIG. 14 RING JUNCTION TUNNEL-DIODE

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as shown in Fig. 14b. In practice, many difficulties have to be overcome in order to achieve this structure. Perhaps the greatest difficulty is getting the alloy dot to alloy completely around the circumference of the SiO dot. GaAs is not wet very well by tin at the temperatures required for good tunnel diode formation, and thus very little spreading takes place. The metal layer deposited on top of the SiO mask helps spreading somewhat. However, the alloying temperatures needed in order to make the alloy dot wet around the SiO dot proved to be too high for the resulting diodes to have good electrical characteristics. Initial results showed the diodes to have excessively high junction capacitance at peak currents of 600 ma. This was not due to the parasitic capacitance introduced by the insulating SiO layer which is only 0.1 pf. The high capacitance results from the excessively high alloying temperature which increases the barrier width and reduces the current density of the resulting diodes. In another attempt to obtain good wetting at lower temperatures 60/40 Sn-Pb alloy dots were used in place of pure Sn. Better wetting (on the basis of the number of units on which the sphere alloyed completely around the SiO mask) was observed but the resulting diodes showed little improvement since this actually allowed for only a very small reduction in alloying temperature.

Other problems were encountered with the adherence of the SiO to the GaAs wafer surface. Best results were obtained using wafers about 2-3 mils thick because thinner wafers tend to warp and pop the SiO dots off during alloying. In spite of the difficulties, diodes were fabricated with this structure and had the typical electrical characteristics shown in Table 2. These are plainly no better than the diodes made by conventional techniques.

TABLE 2

No.	I_p(ma)	I_v(ma)	E_p(mv)	E_v(mv)	R_s(ohms)	C_v(pf)	f_{co}(gc)
1	600	45	270	540	0.25	73	4.1
2	610	60	260	640	0.20	68	5.8

Electrical Parameters of Some Annular Junction Tunnel Diodes

An effort was also made to fabricate a line junction tunnel diode. The technique which was investigated was to evaporate a square insulating layer (silicon monoxide) which contains a small opening (0.003" x 0.006"), and alloying tin to the GaAs through the opening. Subsequent etching to the desired peak current would increase the junction aspect ratio. However, the same problems encountered with the annular junction quickly became evident in this process, and no significant improvement in diode characteristics was observed. Distributed junctions of this type are possible, but more work than is possible under the scope of this contract will be necessary to achieve them.

(c) Diode Fabrication

The diodes for this contract were fabricated by a highly refined straight alloy process. In this process, a pure Sn sphere 0.003" in diameter is alloyed to a Zn-doped GaAs pellet. The resulting tunnel diode is then mounted in a low inductance case as described before, in Fig. 3, and then electrolytically etched to the desired peak current. Extensive testing showed the best range of carrier concentration for the GaAs pellets to be between 8.0×10^{19} and 1.0×10^{20} atoms/cc. The alloying is carried out in a resistance furnace. An extremely fast temperature cycle is used to insure a small barrier width. The cycle must be

altered slightly for each new wafer that is processed. However, once the cycle is determined for a particular wafer, the same cycle can usually be used for the remainder of the pellets from the wafer. The diode is then carefully etched and a pulser is used when taking parameter readings of the diodes in order to avoid degrading them.

Using this technique, 213 gallium arsenide tunnel diodes were made for circuit tests. Table 3 lists typical diode parameters. Although the table shows I_p values ranging from 300 to 700 ma, most of the diodes had $I_p \approx 600$ ma. The other values were chosen for experimental purposes.

TABLE 3

Typical GaAs Tunnel Diode Characteristics

I_p(ma)	I_v(ma)	C_v(pf)	r_s(ohms)	f_r(gc)
350	20	24	.42	7.4
500	35	41	.225	7.4
600	40	38	.26	7.3
600	30	32	.27	8.0
600	35	28	.27	9.2
700	40	42	.25	6.2

(d) Environmental Tests

Temperature - Two units having the initial parameters shown below were subjected to a temperature coefficient test from -55°C to +75°C. The test was carried out in a chamber designed for this purpose. The units were allowed to stabilize for ten minutes at each temperature before the readings were taken. The variation in peak current is shown in Table 4. Fig. 15 shows the variation in valley

TABLE 4

Initial Readings at 25°C

No.	I_p(ma)	I_v(ma)	E_p(mw)	E_v(mw)	R_s(ohms)	C_v(pf)	f_{co}(kmc)
1	600	30	220	610	0.22	46	7.8
2	610	35	230	580	0.22	47	7.5

I_p at Various Temperatures

No.	-55°	-25°	0°	+25°	+50°	+75°	Temp.
1	590	600	600	600	590	585	I_p
2	610	610	610	610	590	580	

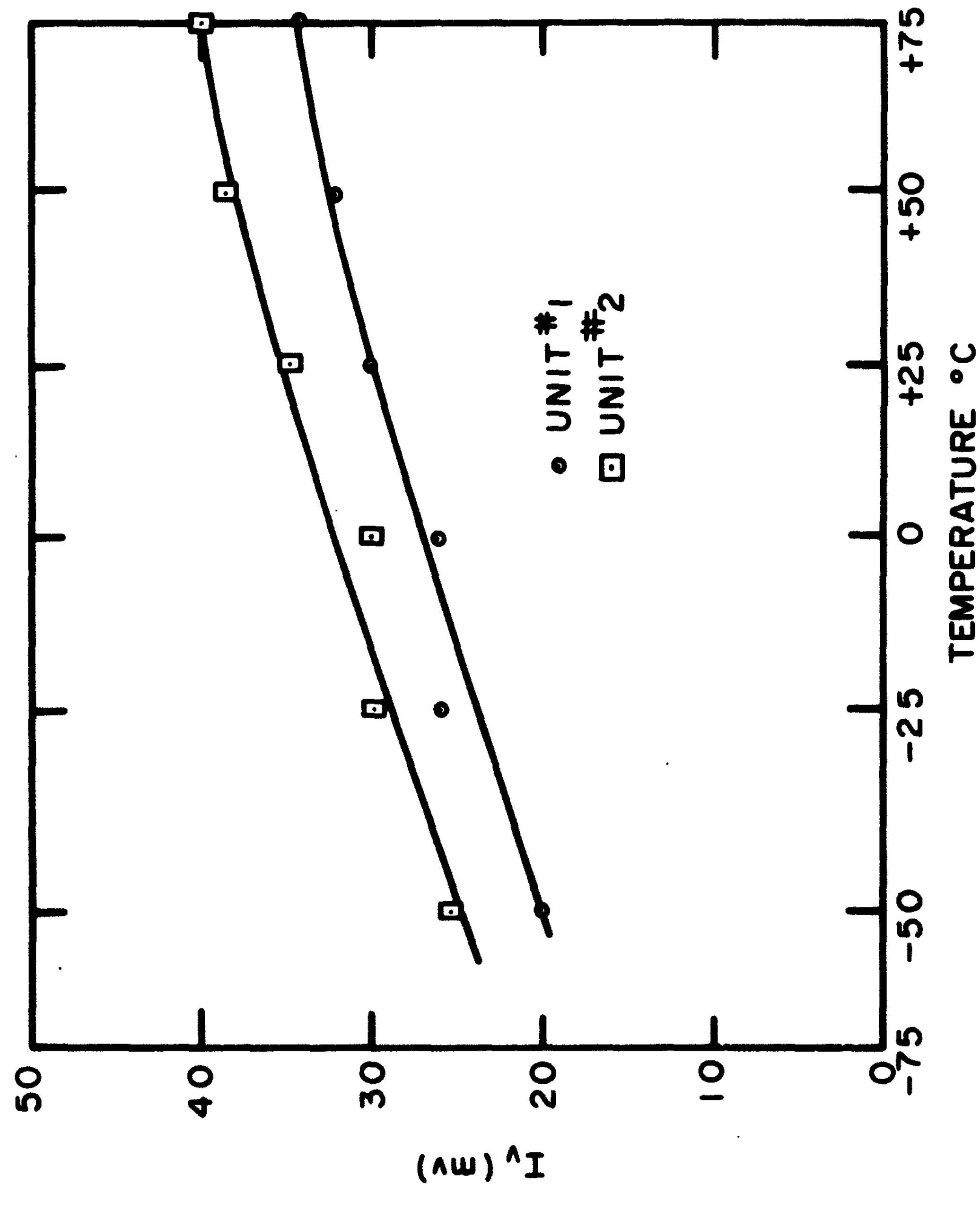

FIG. 15 VALLEY CURRENT VS TEMPERATURE FOR 600 ma TUNNEL-DIODE

current as a function of temperature.

It can be seen that I_p is constant over the temperature range -25°C to +25°C and changes only slightly at the higher and lower extremities of the range.

The variation in I_v is seen to be such that the I_p/I_v ratio is never less than 14:1 for either unit over the entire range.

Shock and Acceleration Tests - One dozen diodes in strip line packages were subjected to a series of centrifuge tests. The units were tested at 1000, 5000, 10,000, 15,000 and 20,000 g's for a period of 15 seconds in both axial and radial directions. Half of the units tested contained a potting compound, GE-SR520. None of the units, either potted or unpotted, showed parameter changes.

Twelve units of the same type as used in the above test were subjected to a 3000 g shock test. None of the units which had been potted (six diodes) failed, while one which had not been potted failed.

(e) Conclusions

A design analysis was made to determine the electrical characteristics of a GaAs tunnel diode required for delivering 25 milliwatts of power at 1.7 gc. This analysis indicated that the diodes should have a peak current of about 600 ma, a junction capacitance on the order of 20-40 pf and a cutoff frequency greater than 6 gc. The requirement for low package inductance led to the development of a new strip line package which has an inductance of about 75 pf. Diodes with these characteristics were fabricated, using a direct alloy process. Special care was taken to reduce series resistance to a minimum. The diodes produced in this manner were used in a strip line circuit to produce over 30 milliwatts at 1.7 gc.

An analytic and experimental study was made of the effect of semiconductor impurity concentration and junction area on cutoff frequency. The

experimental results confirmed the prediction that f_r should increase as the area is decreased by etching. A subsequent decrease in f_r after prolonged etching is explained by the non-uniform distribution of tunnel current across the junction area.

A limited investigation was made of techniques for fabricating distributed (ring and line) junctions. The results were no better than that obtained by conventional direct alloying. However, the scope of this program did not permit as extensive a study of distributed junctions as would be required to achieve a substantial improvement in diode characteristics by this technique.

2. Tunnel-Diode Oscillator Circuits and Results

(a) Introduction

The requirement of 25 mw of rf power from a tunnel-diode oscillator placed a number of constraints on the rf circuit. First, in order to operate the high peak current diodes required for this power output at the desired frequency a very low impedance circuit was required. Secondly, the low value of stabilizing resistor necessary for dc stabilization of the high current diode dictated the placement of the resistor at a point of essentially zero rf voltage in the circuit in order not to drastically reduce the circuit efficiency. Finally, the intended application to radiosondes added the requirement of very low cost. Consideration of these factors led to the choice of a reentrant-ring strip transmission line circuit which had been used in previous tunnel-diode oscillators.[1] Four types of reentrant-ring circuits, differing primarily in the way in which they could be packaged in a geometry suitable for radiosondes, were investigated.

(b) Results of rf Circuit Tests

Circular Ring Circuits - The first type oscillator tested employed a circular reentrant-ring stripline circuit. A sketch of the circuit is shown in Figure 16. Tuning was accomplished by means of 10 pf variable condenser. The tunnel diode was a gallium-arsenide stripline package unit having the following characteristics:

Peak Current	445 ma
Series Resistance	0.3 ohms
Capacitance	29 pf

Curves of power output and frequency of the oscillator versus tuner turns are shown in Figure 17. Similar curves versus bias voltage are given in Figure 18. The

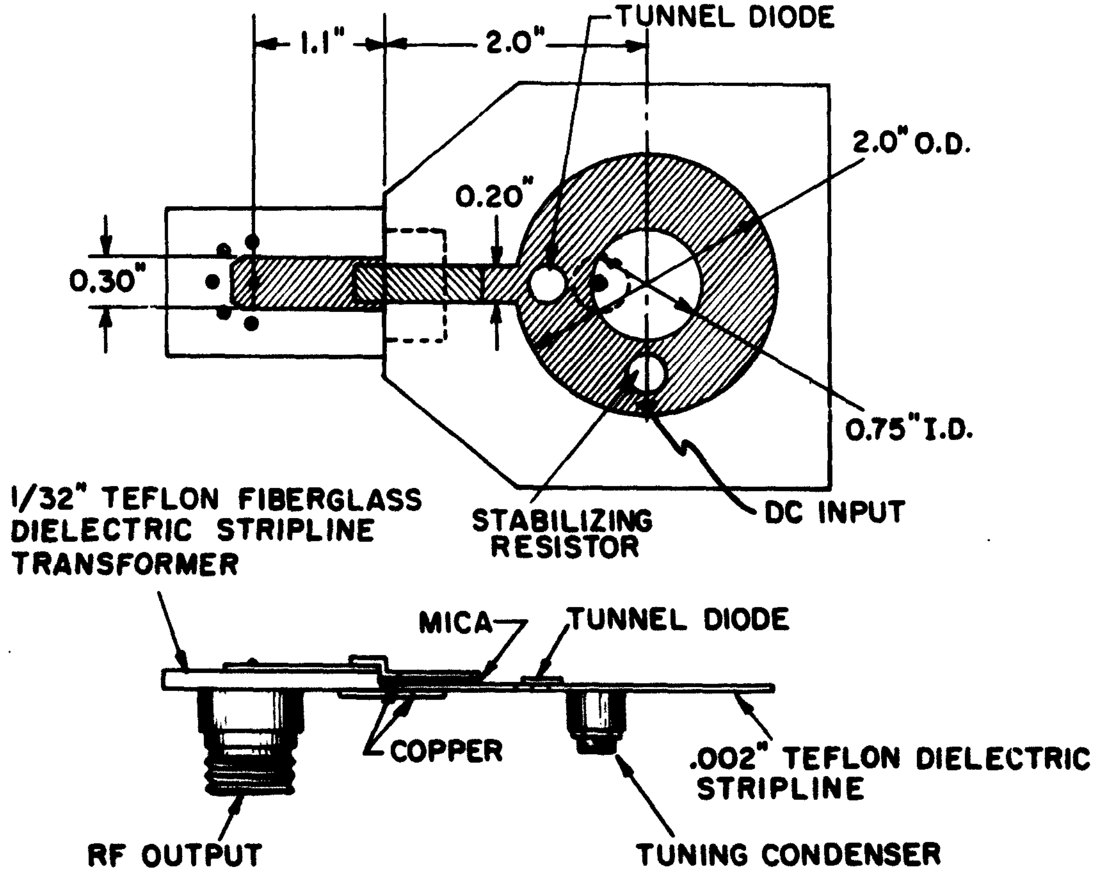

FIG. 16. CIRCUIT FOR BREADBOARD MODEL OSCILLATOR SS 116 SER. NO. 001

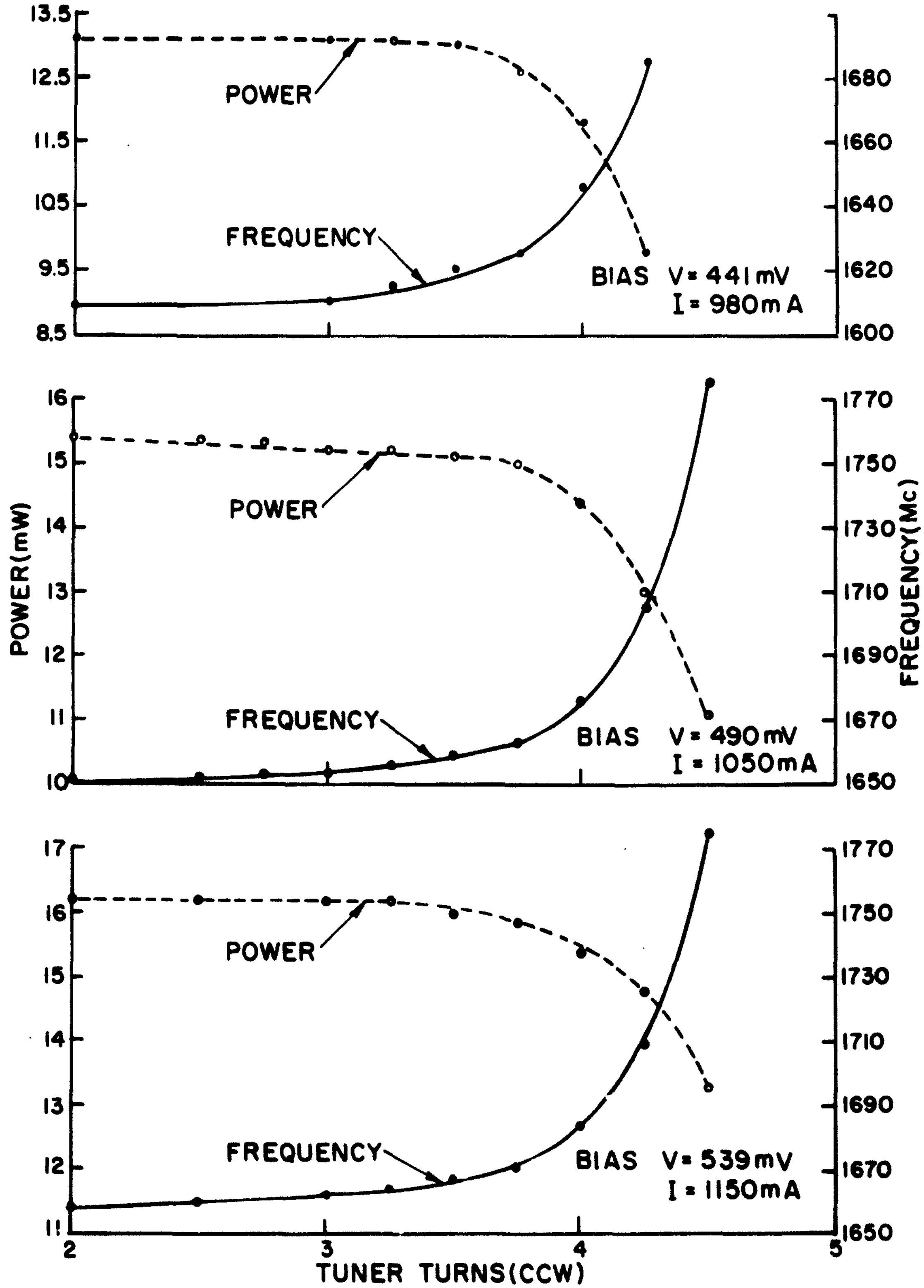

FIG. 17. POWER AND FREQUENCY vs. TUNER TURNS
(SS116 SER. NO. 001)

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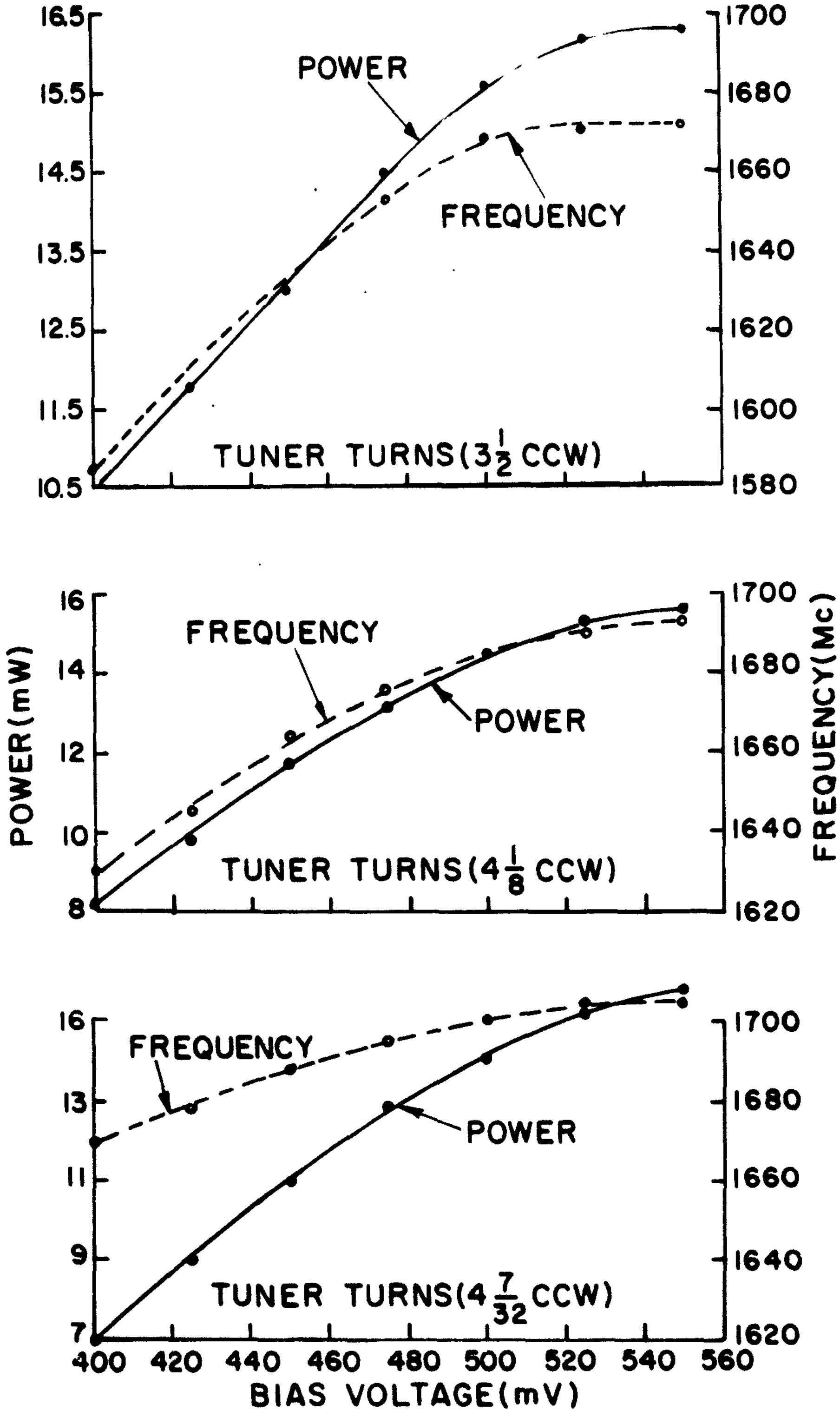

FIG. 18. POWER AND FREQUENCY vs. BIAS (SS116 SER. NO. 001)

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pulling figure of the oscillator at a 1.5 VSWR was 47 Mc. A 10 db isolator placed at the output of the oscillator, reduced this value to 7 Mc.

The five diodes made from a crystal doped to a higher level, ($\sim$ 8 x 10^{19} atoms/cm^3) were tested in a reentrant stripline oscillator circuit similar to that of Figure 16. The three diodes having peak currents of 500 ma were very consistent, giving power outputs of about 25 mw at about 1700 Mc. The 510 ma and 400 ma peak current diodes were lower in both power output and frequency of operation. The reason for this is not obvious from the diode characteristics. The characteristics and test results are tabulated below.

TABLE 5

Tunnel Diode				Bias				
Serial No.	Peak Current ma	C pf	Cutoff Freq. Gc	mv	ma	Power Output mw	Freq. Mc	Impedance Matcher
485-1	500	30	7.4	580	1800	23	1690	No
				580	1830	26	1726	Yes
485-2	510	36	9.5	490	1160	18	1531	No
				485	1170	21	1576	Yes
485-10	500	20	11.0	515	1250	26	1625	No
				540	1250	28	1735	Yes
346-18	500	39	9.9	575	1270	22	1520	No
				565	1270	24	1710	Yes
485-9	400	26	6.9	455	1230	15	1583	No
				475	1260	16	1632	Yes

One oscillator having this type circuit, SS116 Serial No. 001, was delivered as the breadboard oscillator, item 3a under the contract. Work on this type circuit was discontinued due to the difficulty of packaging it in a reasonable size and with the object of attaining a smoother and less critical tuning characteristic.

U-Bar Reentrant-Ring Circuit - This circuit permitted variation of the length of the reentrant ring circuit thus changing both the capacitance and inductance. This gave a smoother tuning characteristic than that of previous circuits where only the capacitance was varied. A sketch of the new circuit is shown in Figure 19 and a photograph in Figure 20.

Tests on the new circuit showed that it did give a smooth tuning characteristic, that it was much easier to adjust the circuit values to cover the required tuning range without frequency jumps or other instabilities. A number of the new circuits of varying dimensions were tried with the best results being a power output of 30 mw. Figure 21 shows a curve of power output versus frequency for one of the circuits using a 600 ma GaAs tunnel diode having a capacitance of 32 pf and a series resistance of 0.27 ohms. The curve shows a power output of 26 to 30 mw over the required frequency range.

Three prototype model oscillators using this type circuit were delivered as item 3b under the contract. A transistor current regulator, which is described in a following section, was used in all to reduce variations in frequency due to a ± 10% change in bias supply voltage. The first two prototype models, SS116 Serial oo2 and 003 were mounted in rectangular packages. Oscillator 002 used a GaAs tunnel diode No. 508-55 which had the following characteristics:

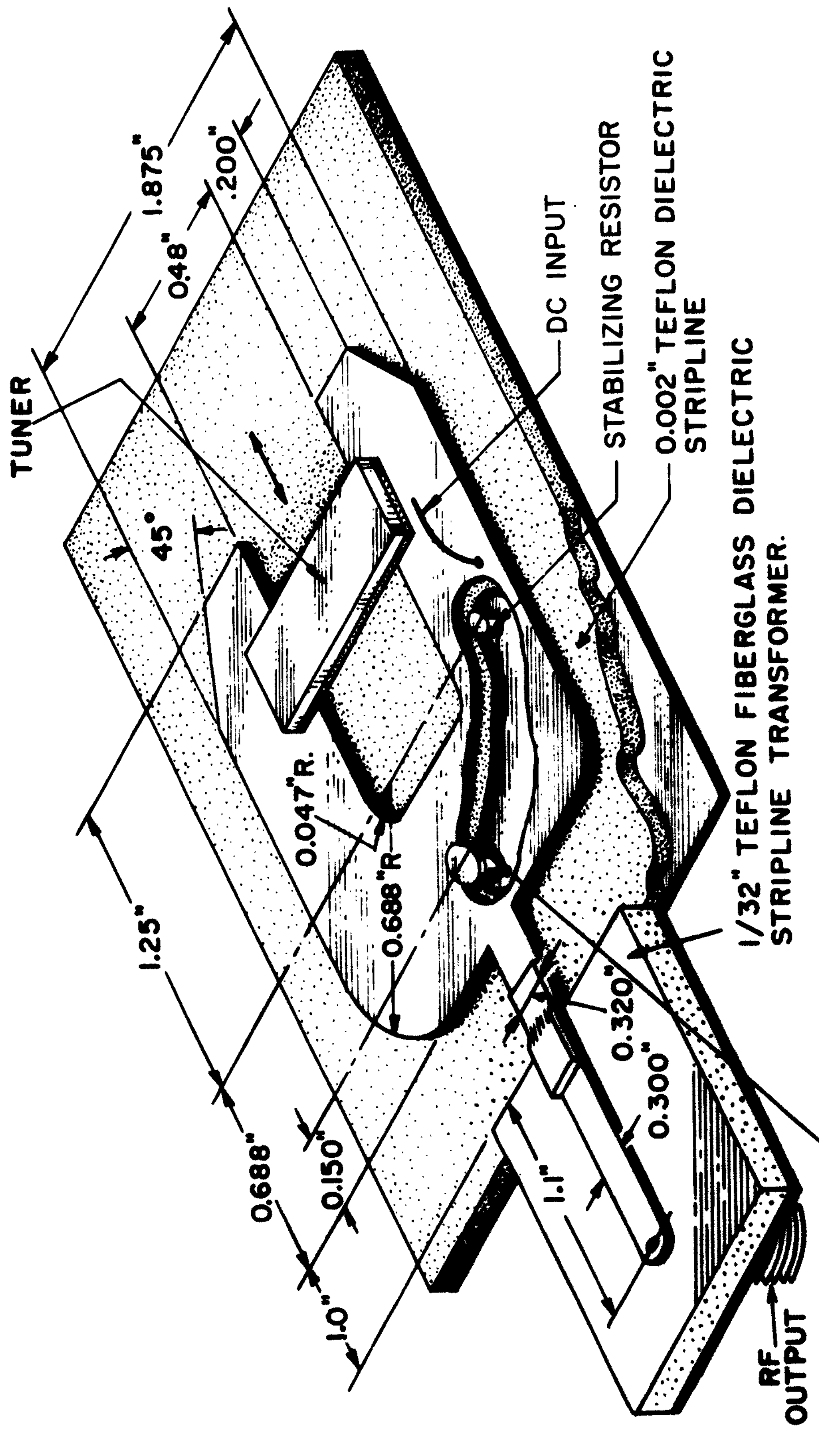

FIG. 19 TUNABLE TUNNEL-DIODE OSCILLATOR

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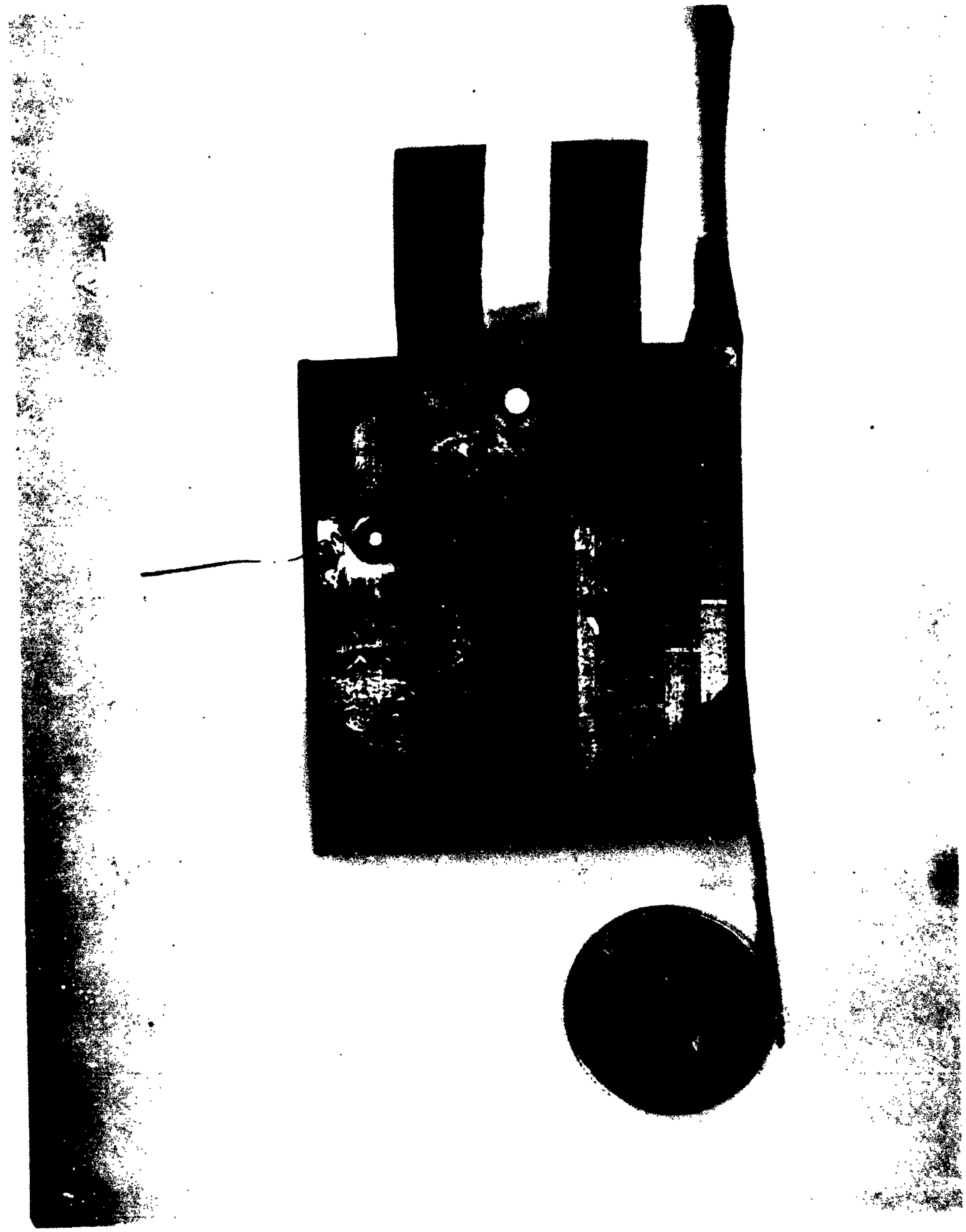

FIG. 20. PHOTOGRAPH OF TUNABLE TUNNEL-DIODE OSCILLATOR

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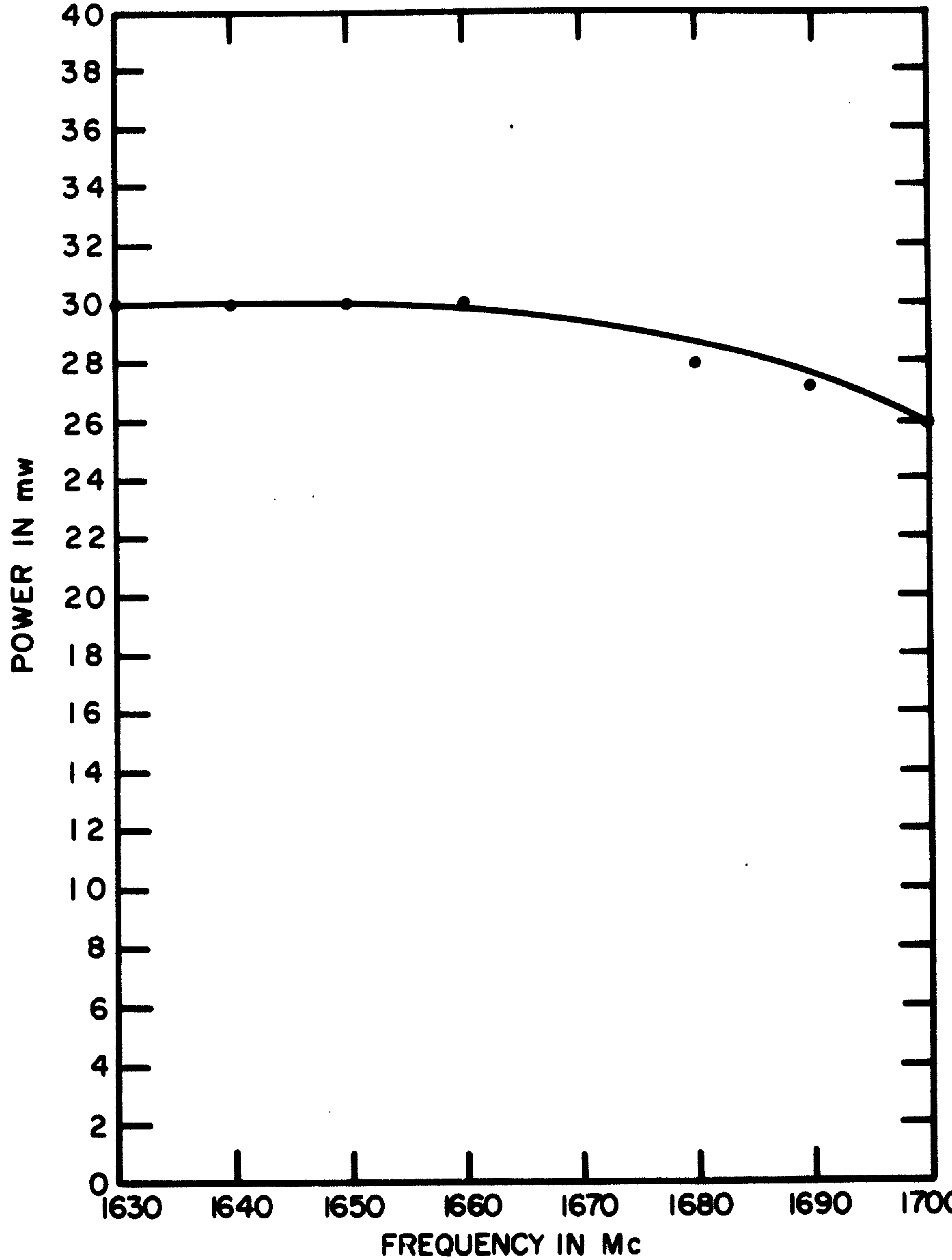

FIG. 21. POWER VS FREQUENCY OF TUNABLE TUNNEL—DIODE OSCILLATOR

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Peak Current	600 ma
Valley Current	35 ma
Peak Voltage	310 mv
Valley Voltage	630 mv
Series Resistance	0.32 ohms
Capacitance	28 pf

Curves of power and frequency versus bias voltage are shown in Figure 22 while Figure 23 gives power and frequency versus tuner turns. The curves show a power output of 18.95 to 20 mw over the 1660 to 1700 Mcs tuning range and also that the ± 2 Mc maximum frequency variation for a ± 10% bias voltage change specification was satisfied at the three tuner settings at which the bias voltage was varied. The pulling figure of the oscillator operated with a 10 db ferrite isolator into a 1.5 VSWR was 10 Mcs.

GaAs tunnel diode No. 568-1 used in oscillator 003, had the following characteristics:

Peak Current	570 ma
Valley Current	40 ma
Peak Voltage	280 mv
Valley Voltage	600 mv
Series Resistance	0.27 ohms
Capacitance	36 pf

Curves of power and frequency versus bias voltage are shown in Figure 24 while Figure 25 gives power and frequency versus tuner turns. The curves show a power output of 22.2 to 24.8 mw over the 1660 to 1700 Mc tuning range and also show that the frequency variation with bias voltage specification was satisfied. The

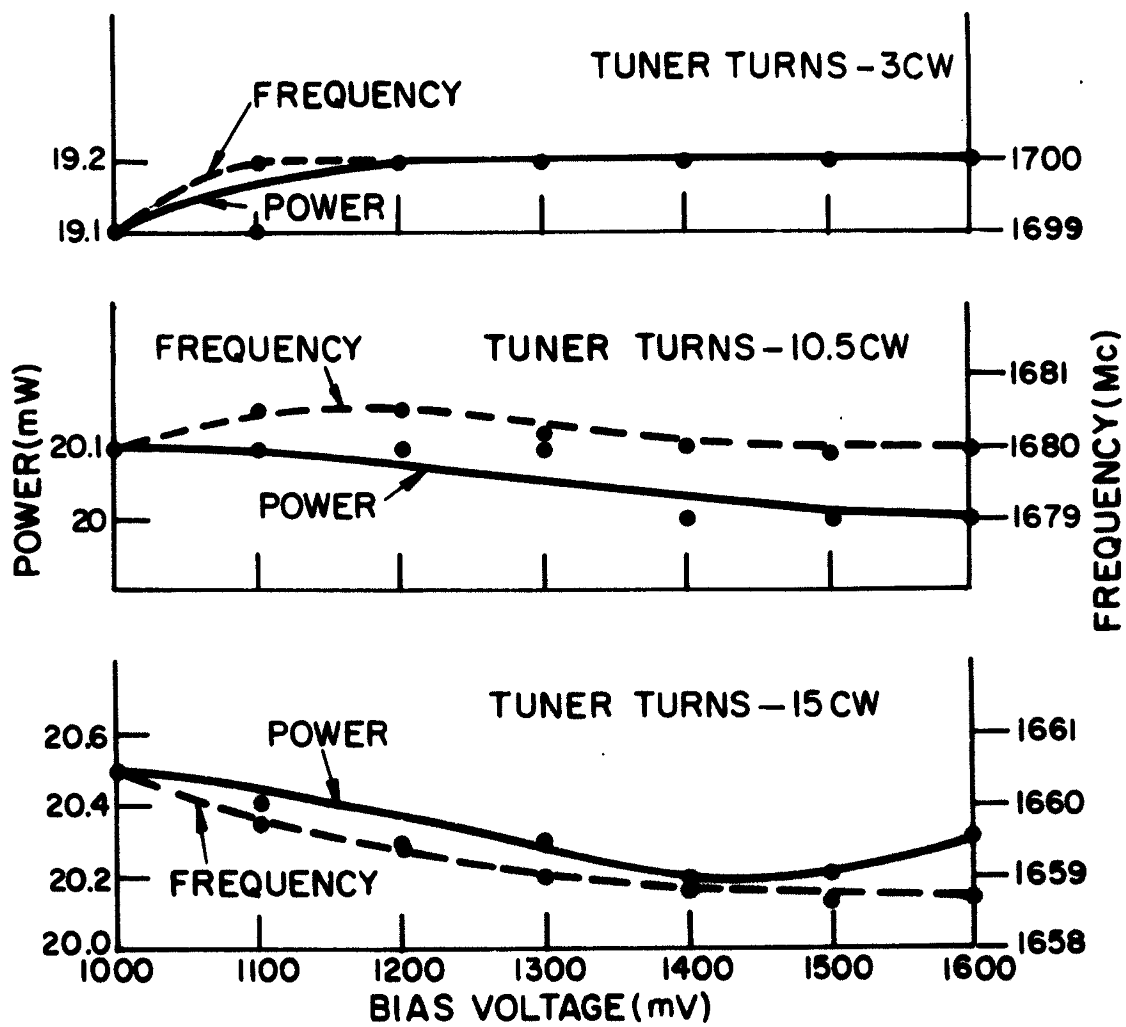

FIG. 22. POWER AND FREQUENCY vs. BIAS VOLTAGE — TUNNEL- DIODE OSCILLATOR SS116, SERIAL 002

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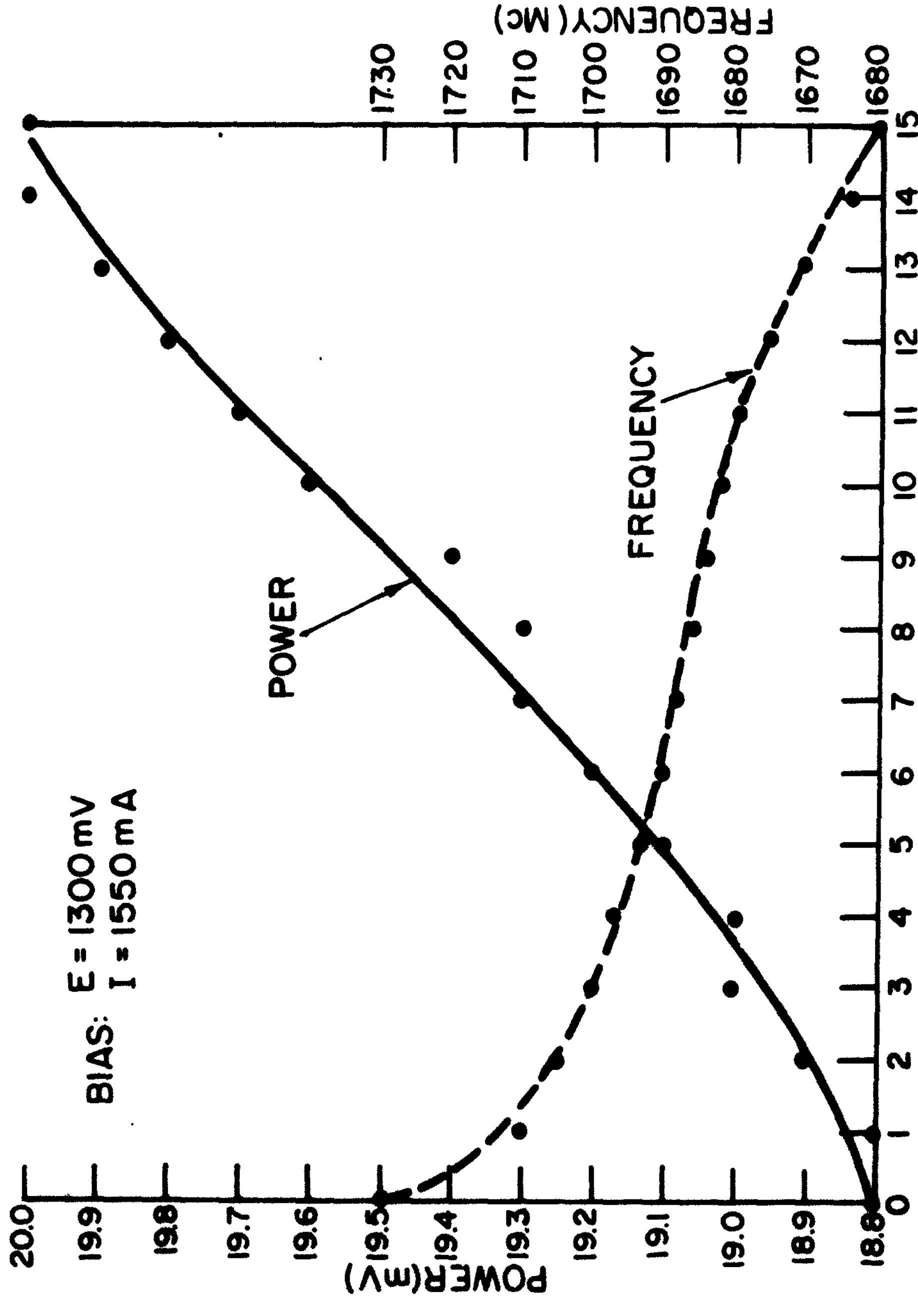

FIG. 23. POWER AND FREQUENCY vs. TUNER TURNS — TUNNEL-DIODE OSCILLATOR SS116, SERIAL 002

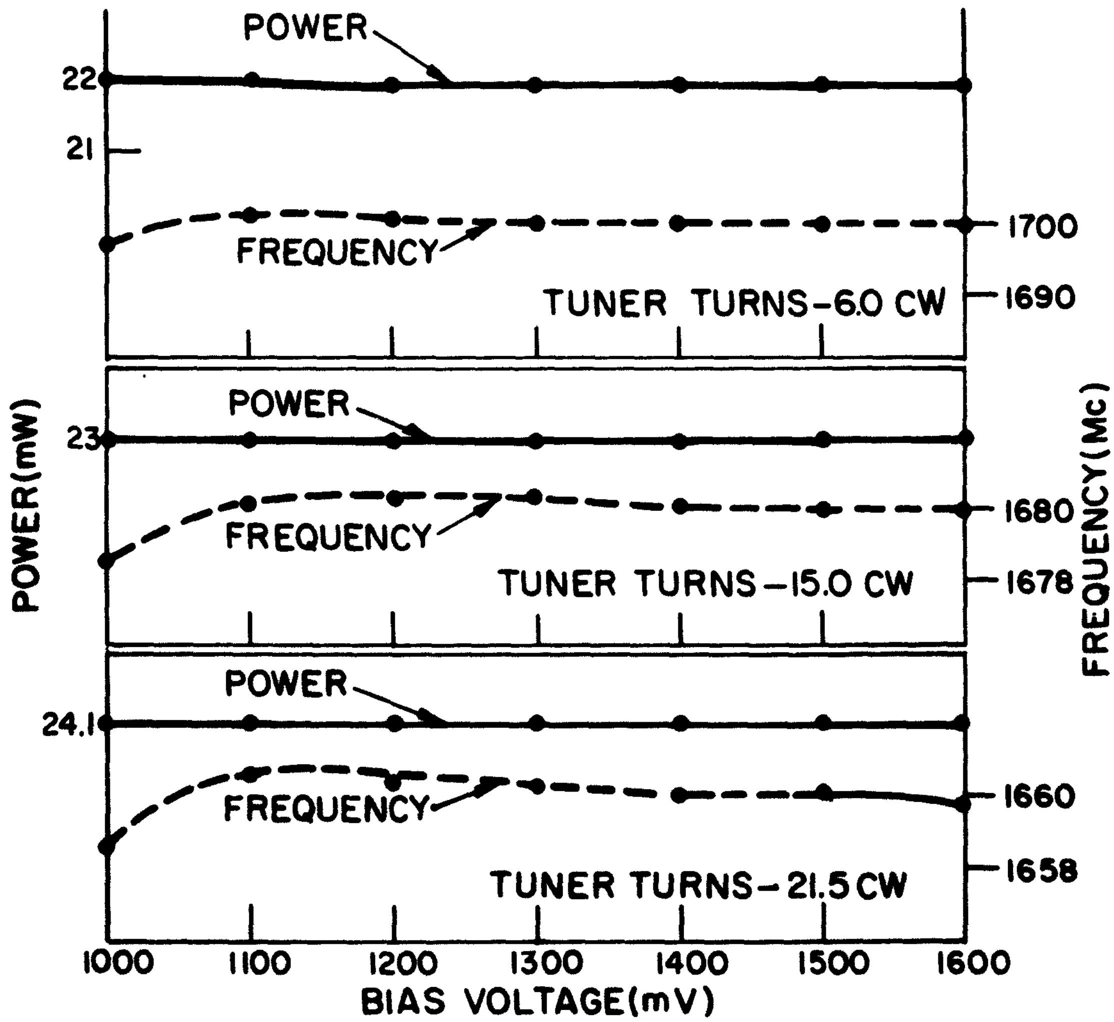

FIG. 24. POWER AND FREQUENCY vs. BIAS VOLTAGE — TUNNEL-DIODE OSCILLATOR SS116, SERIAL 003

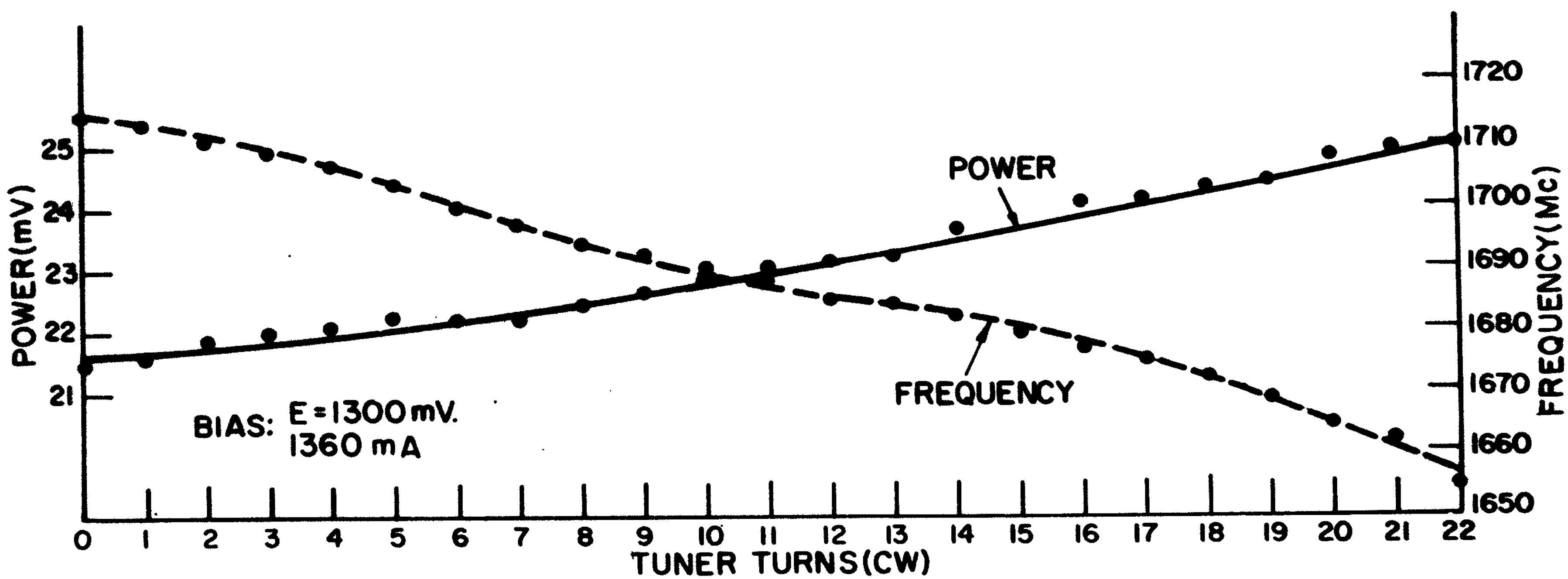

FIG. 25. POWER AND FREQUENCY vs. TUNER TURNS — TUNNEL-DIODE OSCILLATOR SS116, SERIAL 003

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pulling figure of the oscillator operating with a 10 db ferrite isolator into a 1.5 VSWR was 13.4 Mcs. Without the isolator the pulling figure was 160 Mcs.

The third prototype model, SS117 Serial 001, was fabricated in a cylindrical package one and three quarter inches in diameter and six inches long. Curves of power output and frequency versus supply voltage are shown in Figure 26. It will be noted that the power output varied about 0.1 mw and the frequency about 1 Mc for a supply voltage range of 1.1 to 1.6 volts. The jump in the points plotted is due to the fact that these variations in power and frequency are near the limits of resolution of the power meter and frequency meter used for the measurements.

Difficulty in packaging this type circuit in a reasonable package size as well as a probable high cost of the tuning mechanism led to discontinuing work on it.

Oval Reentrant-Ring Conical Circuit - A further investigation was made of oscillator circuits tuned by a miniature variable capacitor. This type tuning was used in the bread-board oscillator described earlier. Due to the difficulty of getting a smooth tuning curve without frequency jumps and power output variations this type of tuning was replaced by the U-Bar ring circuit with a sliding contact. However, the capacitor tuned circuit offered the advantage of much smaller package sizes if this difficulty could be overcome.

A Smith Chart analysis of the impedance transformation through the output transformers indicated that a tuning capacitor at the end of the first quarter wavelength transformer would provide the required change in susceptance with almost constant conductance. Thus the power output should remain relatively constant. An oscillator was made and tested with such a tuning capacitor placement.

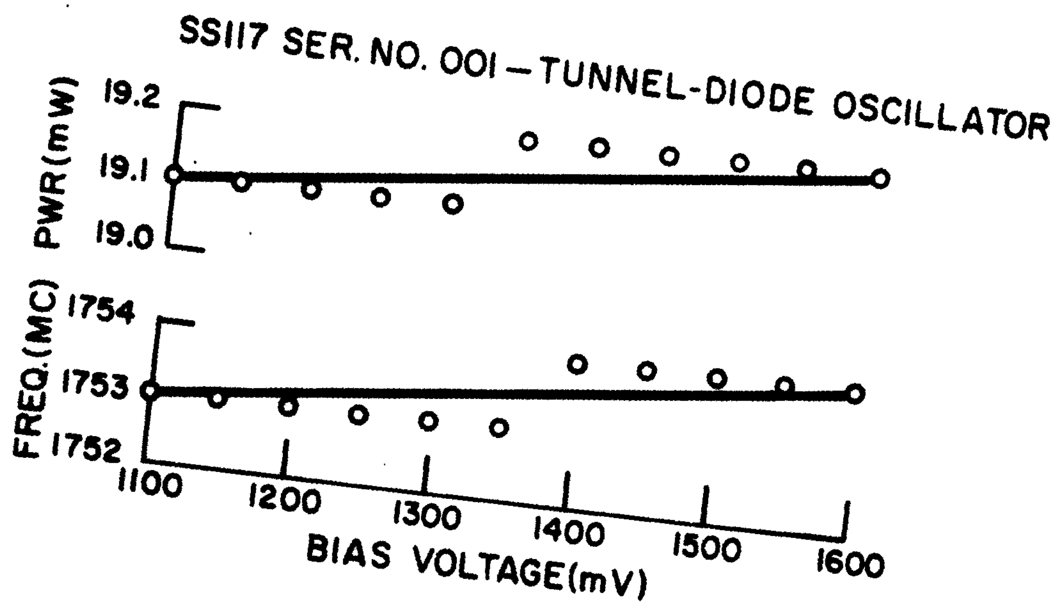

FIG. 26. PLOT OF POWER AND FREQUENCY vs. BIAS VOLTAGE

Figure 27 shows a drawing of the oscillator circuit. The ring circuit portion is 0.002" thick dielectric stripline and is designed so that it can be rolled up into a cone which could form the ground plane of an antenna. A convoluted view is shown in Figure 28; in a unit to be used in a radiosonde the rf connector shown would be replaced by the radiosonde antenna. A curve of power output versus frequency for this oscillator is shown in Figure 29. A tuning range of 1660 to 1770 Mc was obtained. Over the upper 80 Mc portion of this range the power output variation was less than 1 mw.

Cylindrical Ring Circuits - A second type of circuit capable of being packaged in a small volume was designed. This three dimensional ring or cylindrical ring circuit is shown in Figure 30. The circuit consists of a parallel-plate transmission line made of 0.002 dielectric thickness stripline. The ends of the transmission are joined by rolling the circuit into a ring. A possible advantage of this circuit is that all the current paths around the ring are the same length; thus the current should be distributed more uniformly across the transmission line than in the case of the two dimensional ring circuits where the current path length varies with the radius from the center of the ring. This should give lower losses and lower parasitic reactance. This circuit could be tuned in the same manner as the one in Figure 27, i.e.; with a variable capacitor at the end of the first quarterwave transformer section.

A number of tests were made on oscillators using the cylindrical ring circuit. It was found that it is not necessary to join the two ends of the circuit since the joint is at a minimum current-maximum voltage point. Therefore the same operation is obtained with the ends left open and the problem of packaging is simplified. Also the ends of the circuit may be trimmed to adjust the frequency to the proper range. Power outputs of 30 mw were obtained in several cases;

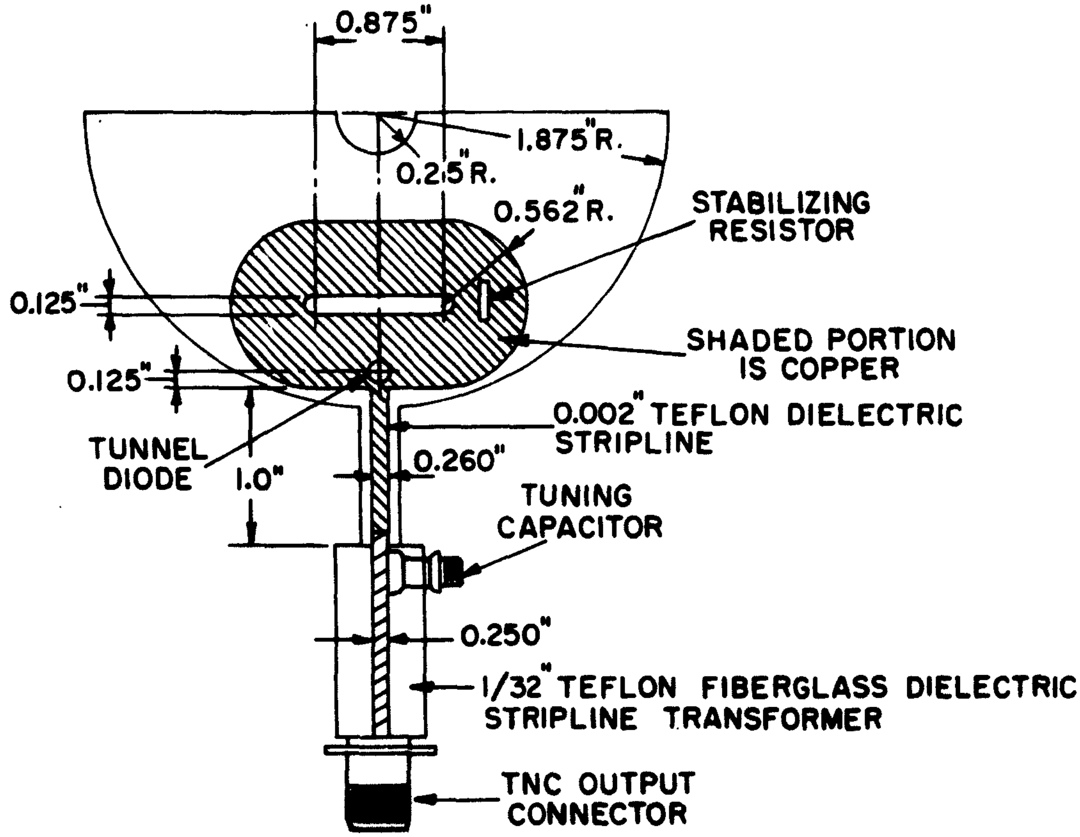

FIG. 27. CAPACITOR TUNED TUNNEL-DIODE OSCILLATOR. EVOLVED VIEW

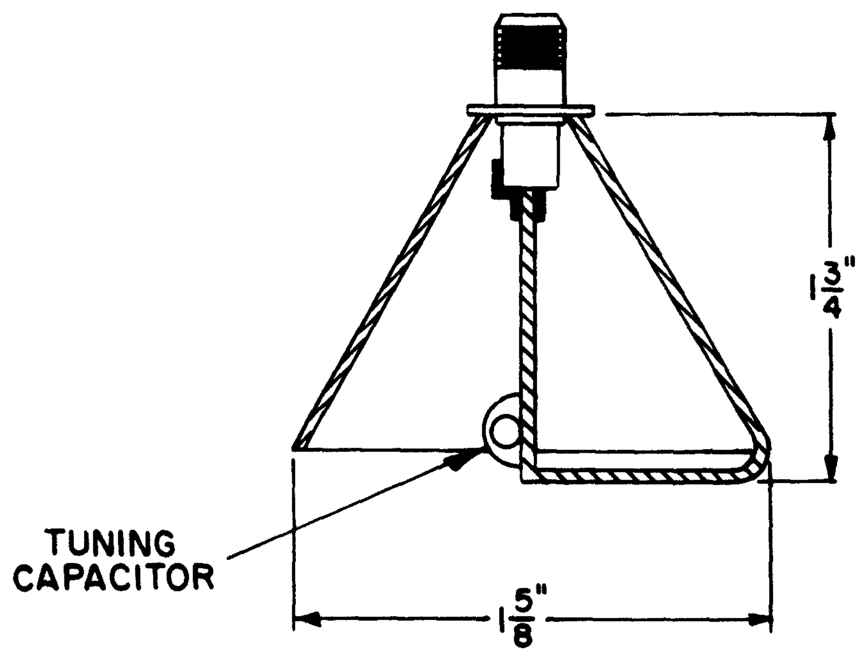

FIG. 28. CAPACITOR-TUNED TUNNEL-DIODE OSCILLATOR. CONVOLUTED VIEW

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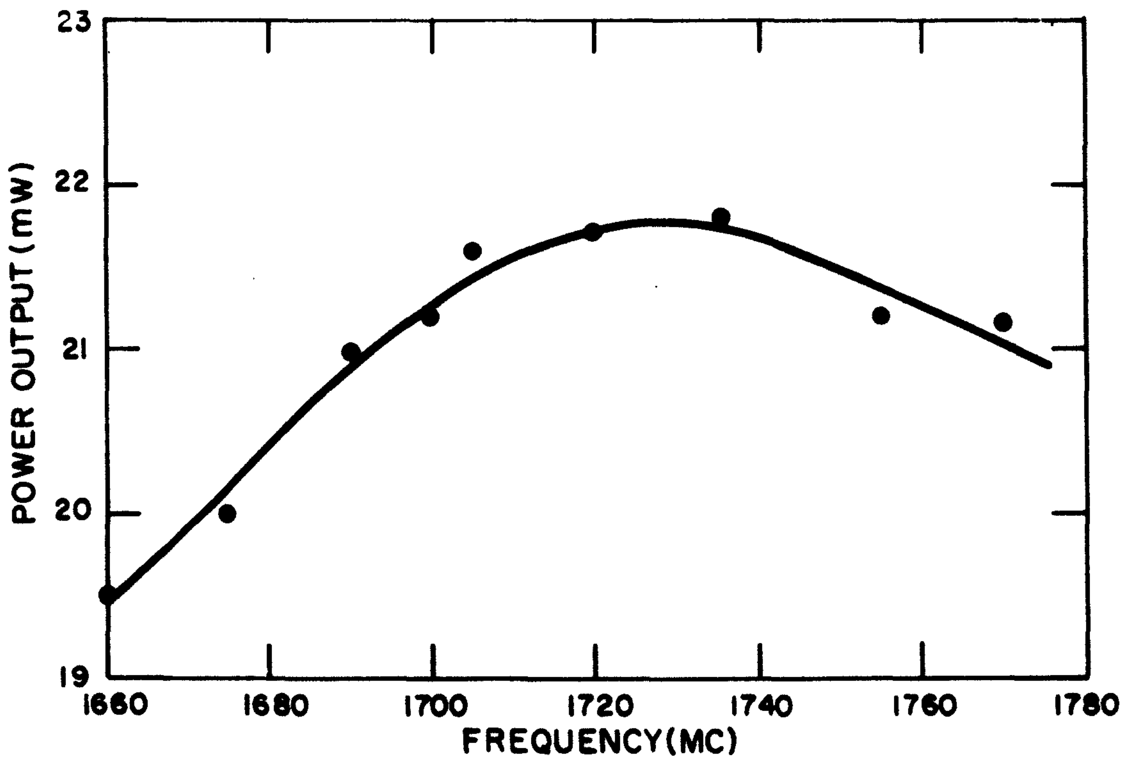

FIG. 29. POWER OUTPUT vs. FREQUENCY CAPACITOR TUNED TUNNEL-DIODE OSCILLATOR

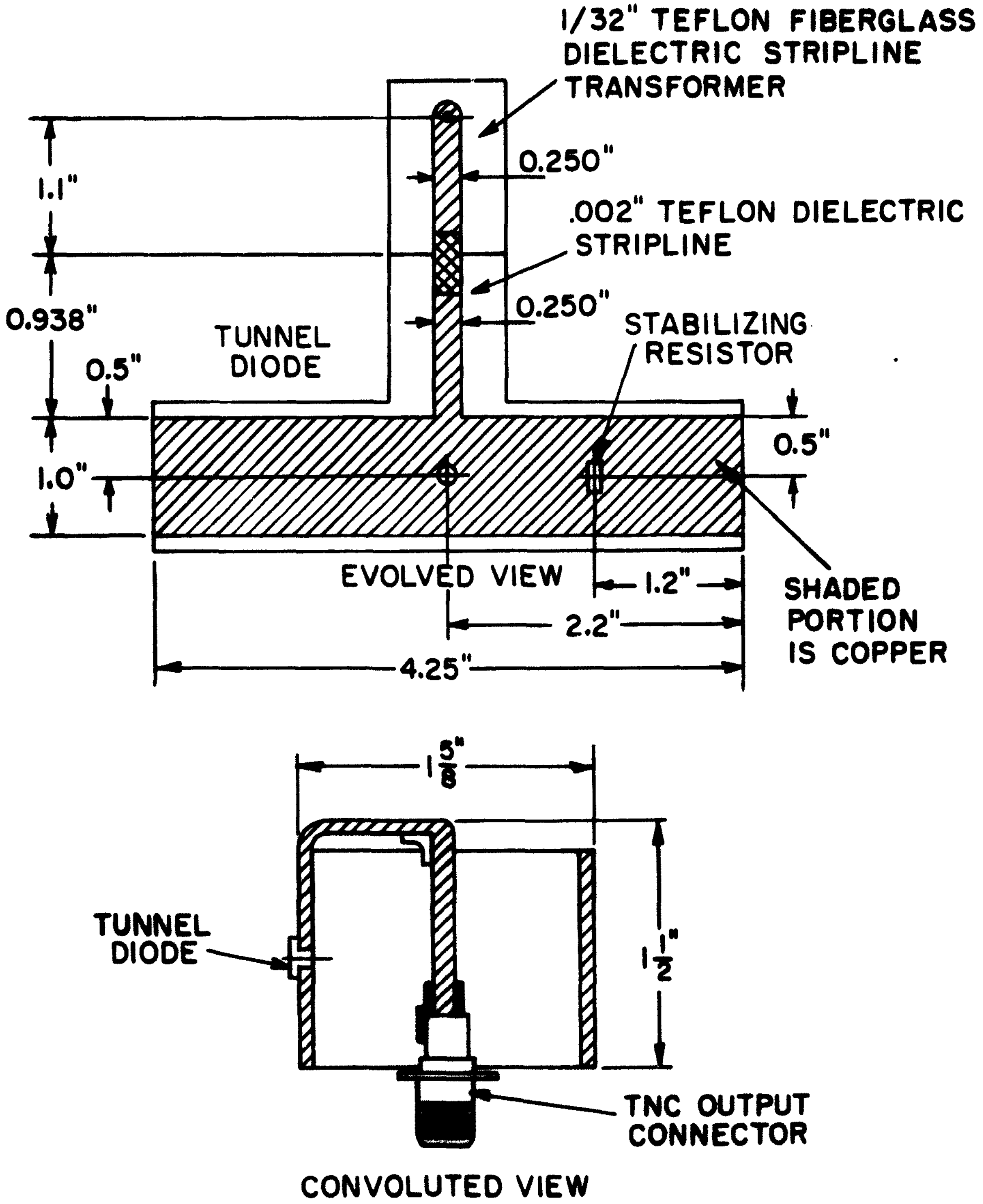

FIG.30 CYLINDRICAL RING CIRCUIT

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however, with the oscillators loaded to produce this maximum output, the pulling figure and the frequency variation with bias voltage were in excess of 100 Mc.

The possibility of varying the frequency range by trimming the ends of the circuit and somewhat more flexibility in packaging led to the choice of the Cylindrical Ring over the Oval Reentrant-Ring circuit for the Developmental Model oscillators.

(c) Stabilizing Resistors

During the early phases of the program a considerable amount of difficulty was experienced with the stabilizing resistors used to fix the dc bias point of the tunnel diode in the negative resistance range of the diode characteristic. For proper operation of the oscillator it was necessary that the resistor have a low inductance thus limiting the size of the resistor, that it have a low resistance (0.4 to 0.8 ohms) and that it be able to dissipate about one watt. The first resistors used were made of a thin film of silver loaded conducting epoxy. It was difficult to get the precise amount of silver and the uniformity of silver distribution to give a reliable resistor. In some cases the resistor failed due to high currents in limited areas burning out part of the resistor. In other cases the resistor did not fail but current paths rapidly made contact and broke contact causing jitter in the frequency and amplitude of the oscillator. None of the companies making film resistor could furnish the dissipation per unit area required.

Later in the program resistors were made using a Dupont resistive glaze coated on ceramic. These were a great improvement. Toward the end of the program the International Resistance Company furnished resistors using their glaze coated on aluminum oxide. The resistors consisted of a 1/8" by 1/8" by

0.010" thick piece of alumina with the glaze resistor coated on one face and deposited silver contacts on two opposite edges. These resistors proved reliable and eliminated the jitter problems.

(d) Current Regulation

The objective specifications for the oscillators provided that the frequency change should be less than ± 2 Mc when the supply voltage was varied ± 10%. Typical 25 mw L-band oscillators exhibited frequency changes of up to 100 Mcs for this supply voltage variation. In order to reduce this frequency change a simple transistor regulator, the circuit of which is shown in Figure 31, was designed. The circuit employs an inexpensive 2N301 transistor operated at fixed base bias to give a current output which changes very slowly with voltage variation. Some selection of transistors is necessary (25% of those tested have not operated properly in the circuit) for operation at the low supply voltage (1.1 to 1.6 volts from the supply, giving about 0.5 to 1.0 volts across the transistor). However, other transistor characteristics, such as maximum voltage, could be relaxed so that no appreciable increase in cost is expected.

Several oscillators were tested using the regulator and in all cases the ± 2 Mcs frequency variation for a ± 10% change in supply voltage was easily met. This type of current regulator was used in the three prototype oscillators delivered on the contract. The performance under varying bias supply voltage for these units was shown in the preceding Figures 22, 24 and 26.

When an oscillator using this current regulator was tested under varying ambient temperatures, however, a large frequency shift and power drop occurred at an increase in ambient of 10°C and the oscillator ceased to oscillate at 20° above room temperature. Attempts to temperature compensate the regulator circuit using thermistors results in only moderate improvement. The germanium transistor was

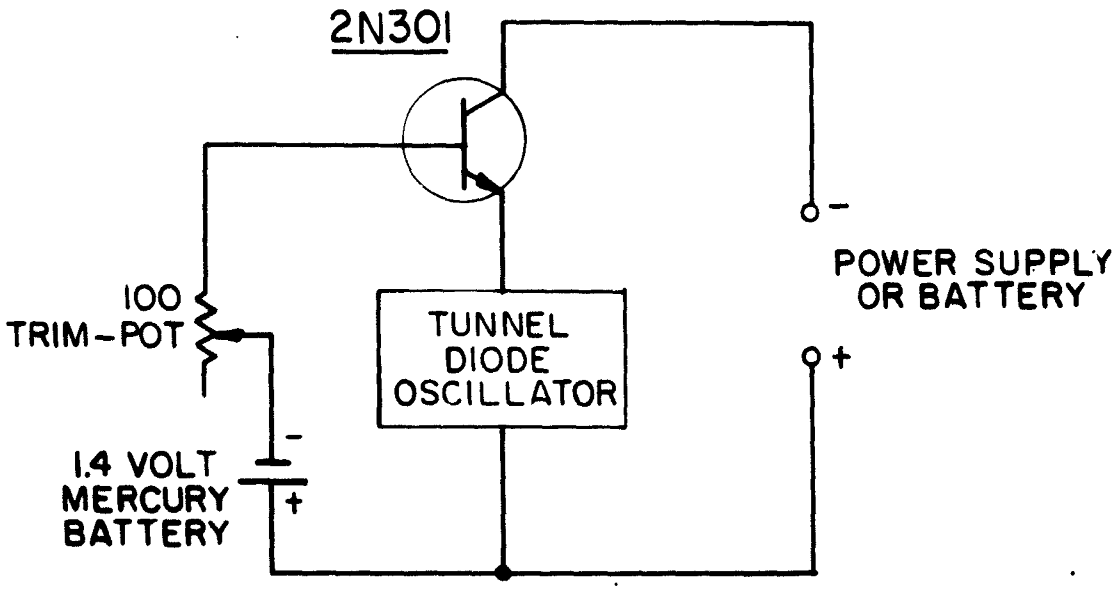

FIG. 31. TRANSISTOR CURRENT - REGULATOR FOR TUNNEL-DIODE OSCILLATOR

replaced by a type 2N1485 silicon transistor. A frequency change of 45 Mc occurred in increasing the ambient from room to 75°C. A thermistor was added in a first attempt to temperature compensate the regulator. This resulted in fairly good operation above room temperature (a frequency change of 3 to 6 Mc depending upon the supply voltage at +75°C ambient). When the ambient temperature was reduced, however, the frequency changed very rapidly and the oscillator stopped oscillating at around 0°C. A test of the mercury battery used to bias the transistor regulator showed that the voltage dropped from 1.29V at room to 0.49 volts at -5°C.

Thus, although the transistor regulator described has reduced the frequency change with supply voltage variations to within the specified limits at room temperature, it has not been satisfactory at low ambient temperatures. This is because the transistor operates at a fixed bias supplied by a battery and at low temperature the change in bias battery voltage is so great that not only the frequency changes are excessive but the tunnel diode oscillator ceases to oscillate due to large change in transistor current.

For this reason effort was devoted to developing a regulator which does not require a bias battery. Tests were made on the regulator shown in Figure 32. In this circuit an increase in the 1.5 volt supply voltage caused an increase in base current of the 2N1700 transistor and thus its collector current increases. This results in a decrease in the base current of the 2N1485 which reduces its collector current thus compensating for the increase in current due to the supply voltage rise. Using this regulator the required specifications on frequency shift were satisfied at room temperature, and the variation in current for other ambient temperatures were sufficiently small to offer good possibilities for compensation by means of temperature sensitive resistors.

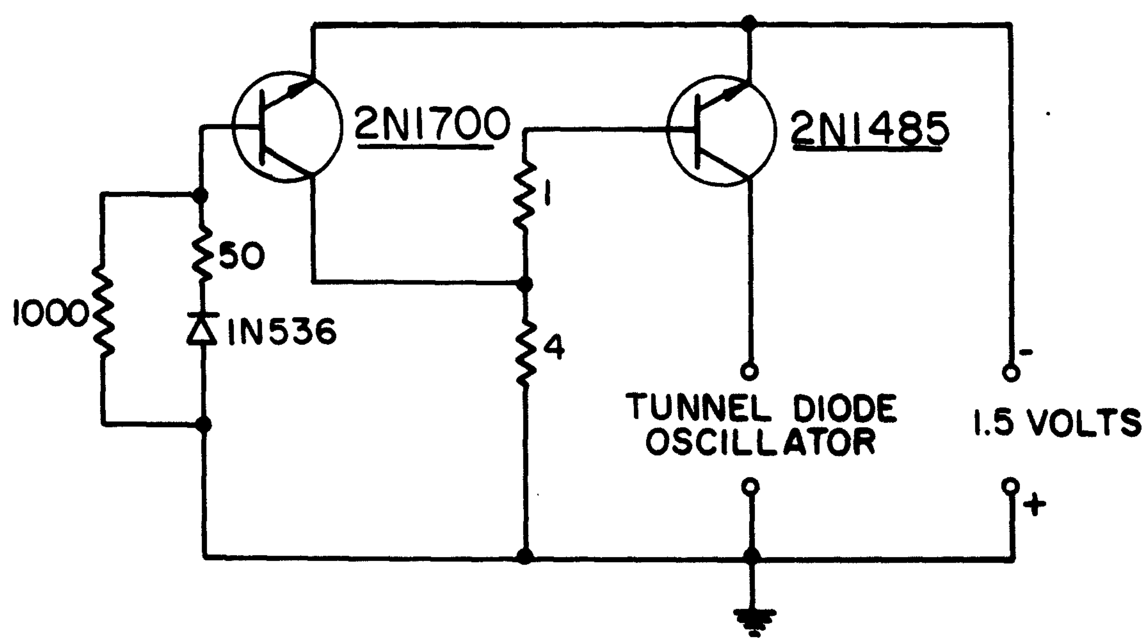

FIG. 32. TRANSISTOR REGULATOR

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(e) Modulation

The tunnel-diode oscillators were easily modulated to deviations up to a few megacycles by varying the bias supply voltage a few millivolts.

A photograph of the output spectrum of oscillator SS116, Serial 002, operating unmodulated at 1680 Mcs with 20 mw output power is shown in Figure 33. The spectrum analyzer dispersion was 200 kc per centimeter division. The oscillator was then frequency modulated using a square wave of 1000 cps frequency and 15 mv amplitude. The spectrum is shown in Figure 34 (200 kc per centimeter dispersion). The input circuit to the transistor regulator distorted the square wave somewhat which is probably the reason for the small spikes in the spectrum between the main spikes.

A transistor modulator circuit was developed suitable for operation from the sensing units in a radiosonde transmitter. The modulator met the specifications on pulse width and repetition frequency for the specified sensor resistance values. A breadboard unit was fabricated and delivered on the contract. The circuit diagram is shown in Figure 35.

(f) Developmental Model Oscillators

The cylindrical ring circuit was chosen for the developmental model oscillators. Three developmental oscillators were made and delivered on the contract. One, S116 Serial 005, was heavily coupled to the output load to give maximum power. The power and frequency versus tuner turns and bias voltage are shown in Figure 36. A power output of 29 mw at 1680 Mc was attained; however, due to the heavy coupling the unit was sensitive to power supply impedance and would not operate stability when connected to the current regulator circuit. The other two units, S116 Serial numbers 004 and 005, were less heavily coupled to the load

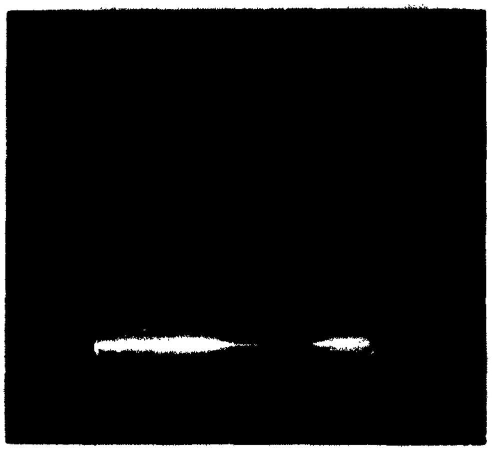


FIG. 33. SPECTRUM OF OSCILLATOR SS116 SERIAL 002 BIAS 1.4 VOLTS, POWER OUTPUT 20 mw, FREQUENCY 1680 Mc SPECTRUM ANALYZER DISPERSION -200 kc/cm

FIG. 34. SPECTRUM OF MODULATED OSCILLATOR SS116 SERIAL 002 MODULATION 15 mv AT 1000 CYCLES PER SECOND SPECTRUM ANALYZER DISPERSION -200 kc/cm

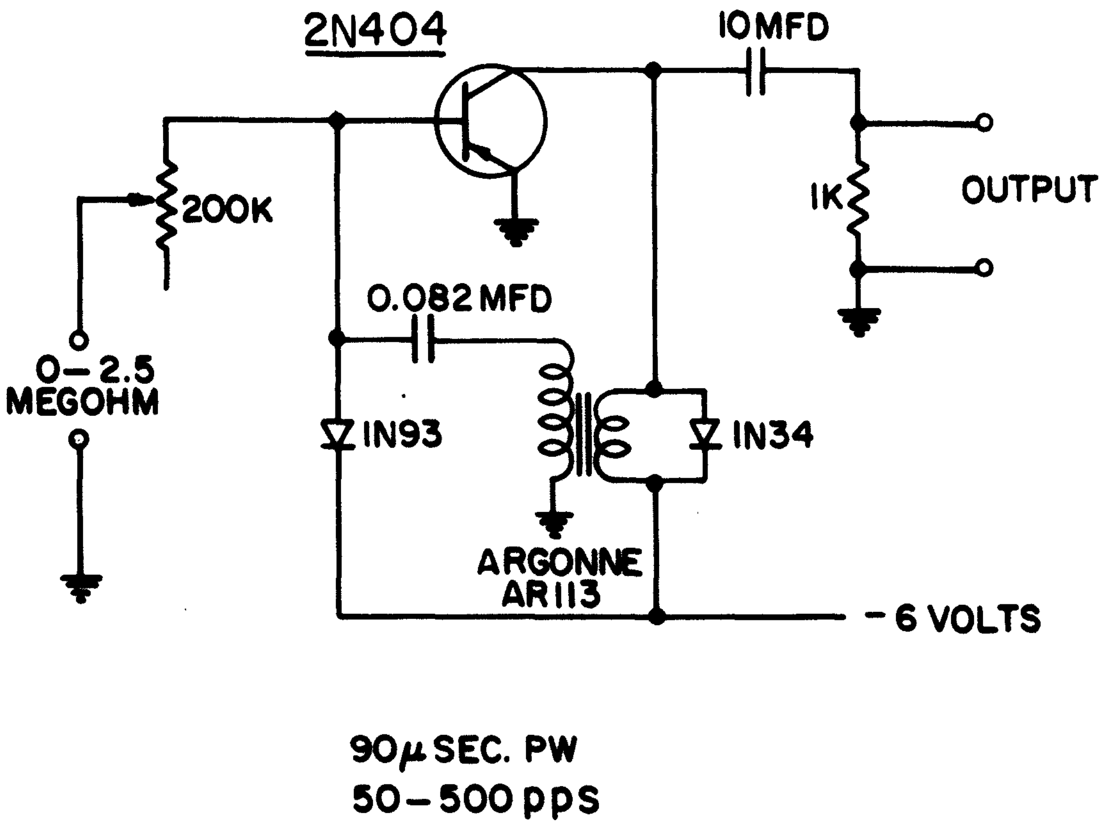
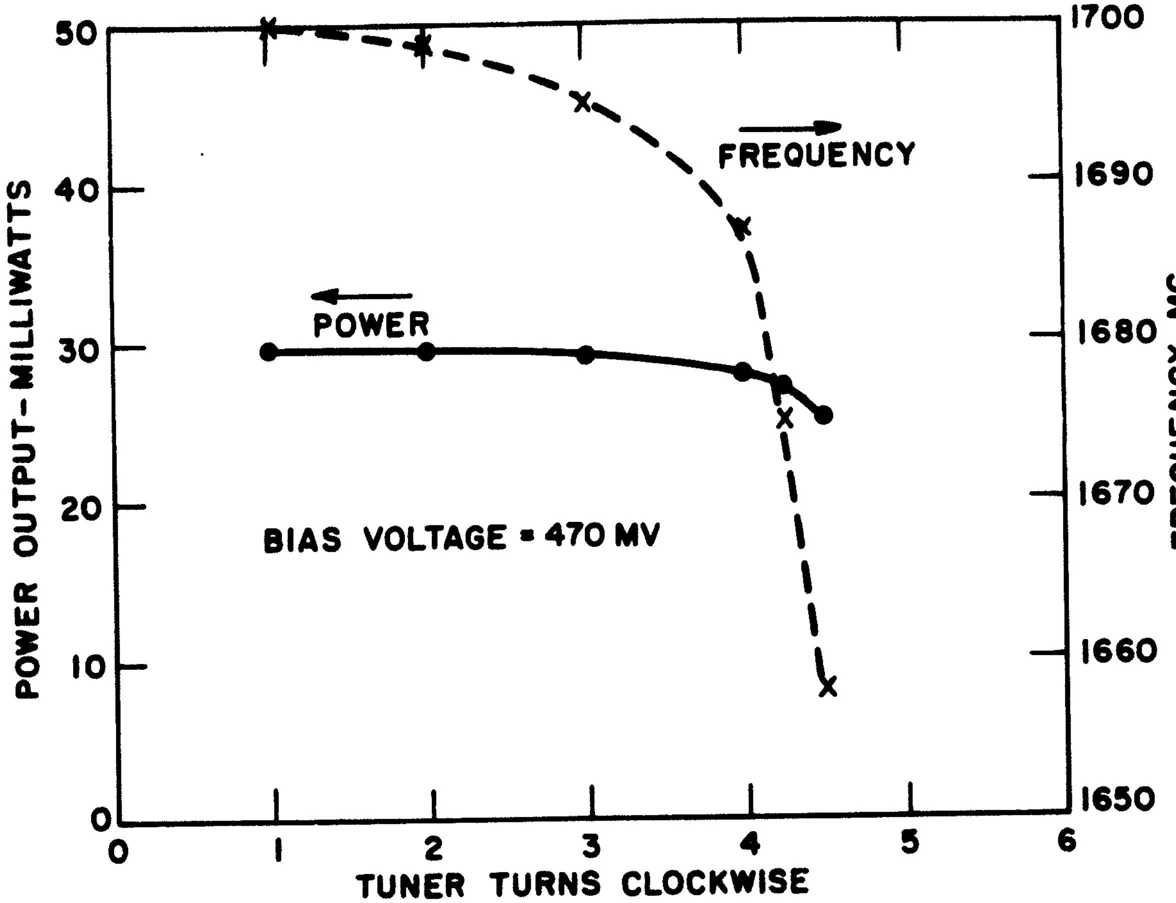


FIG. 35. MODULATOR



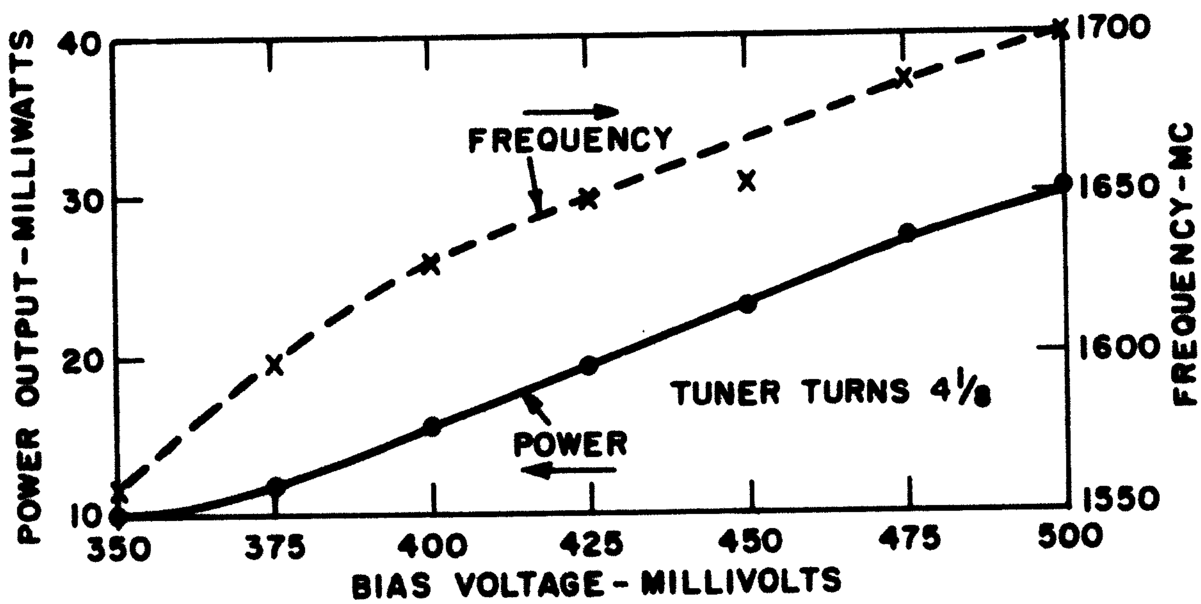


FIG. 36 POWER OUTPUT AND FREQUENCY TUNNEL DIODE OSCILLATOR S-116 SERIAL 005

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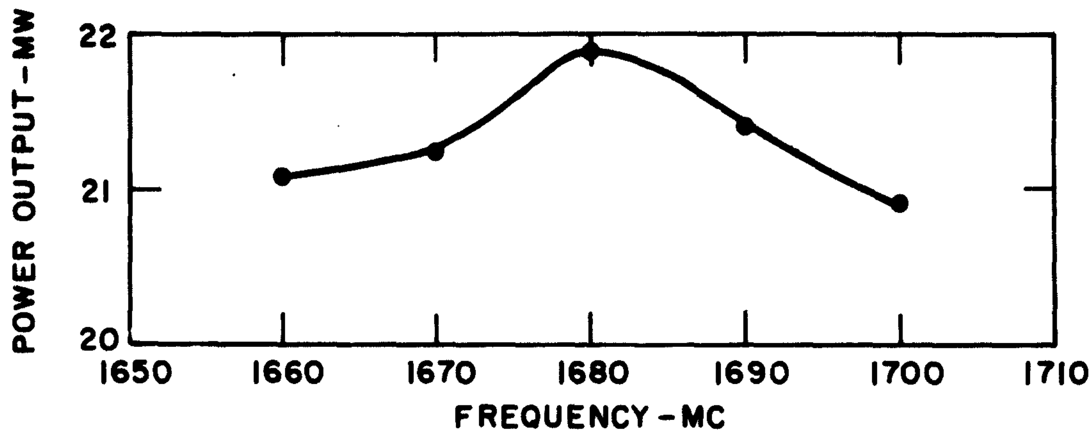
and operated satisfactorily with the current regulator. Due to the reduced coupling the power output was reduced to 18 to 22mw. Curves of power output and frequency versus tuner turns and supply voltage are shown in Figures 37 and 38. The units were packaged in cylindrical packages including the current regulators. A photograph is shown in Figure 39. Other pertinent data on the units was as follows:

Serial No.	004	006
DC Voltage	1.5 volts	1.5 volts
DC Current	1.22 amperes	1.36 amperes
Pulling Figure (no isolator)	70 Mc	44 Mc
(With 10 db isolator)	8 Mc	7.5 Mc

An ambient temperature test was run on Serial No. 004 and the unit showed a frequency variation of 75 Mc over the -55°C to +75°C range. In order to show that this was not due to the current regulator the same test was run on a similar unit without a current regulator. The frequency change was even greater on this unit. At room temperature the frequency was 1660 Mc; at +75°C, 1620 Mc and at -50°C, 1750 Mc. It did not appear feasible to compensate for such frequency changes through compensation in the current regulator and rf compensation directly on the oscillator circuit appeared beyond the scope of the remaining effort available on the contract. Furthermore the development of relatively low cost overlay transistors capable of watts of power at 500 Mc made a transistor oscillator frequency multiplier practical. For this reason RCA proposed substitution of such units for the remaining three developmental models. This proposal was accepted by the contracting agency resulting in the units described in the following section.



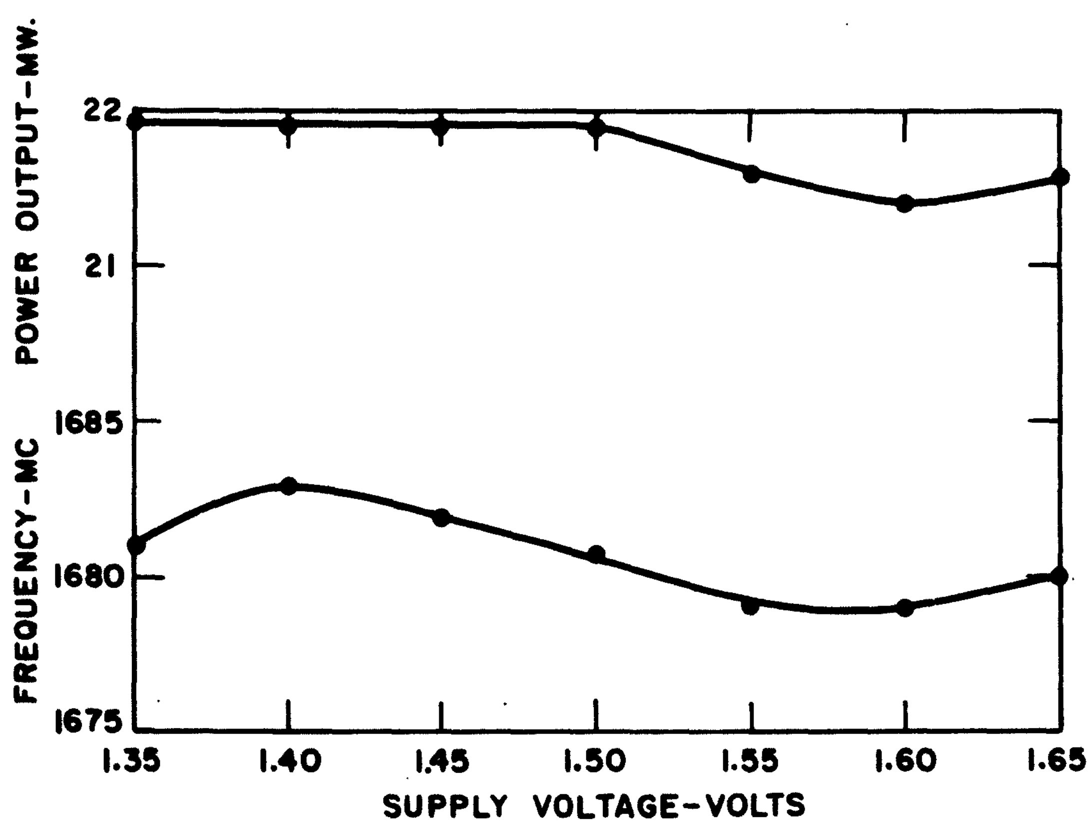


FIG. 37 POWER OUTPUT AND FREQUENCY TUNNEL DIODE OSCILLATOR S-116 SERIAL 004

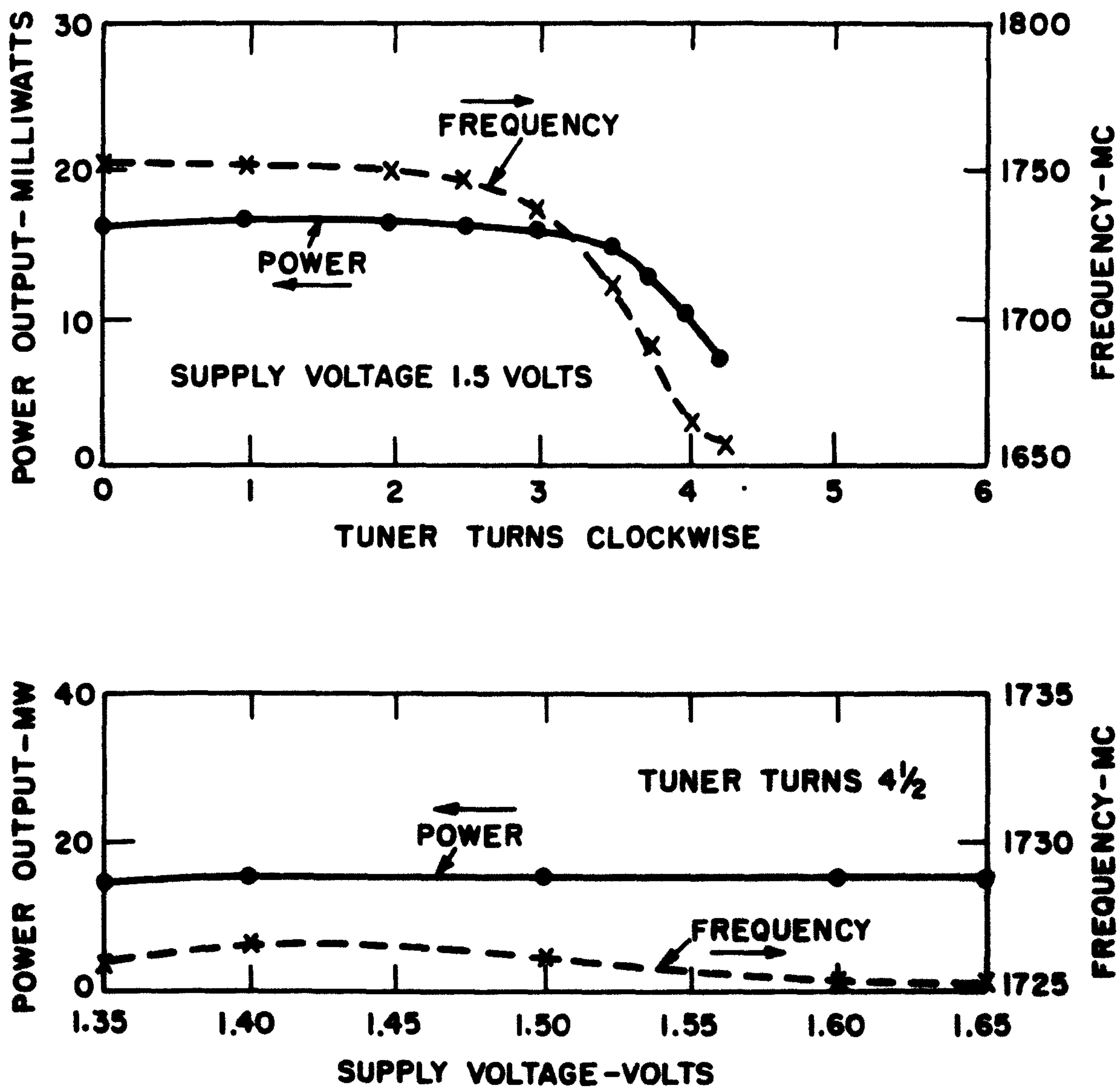


FIG.38 POWER OUTPUT AND FREQUENCY TUNNEL DIODE OSCILLATOR S-116 SERIAL 006.

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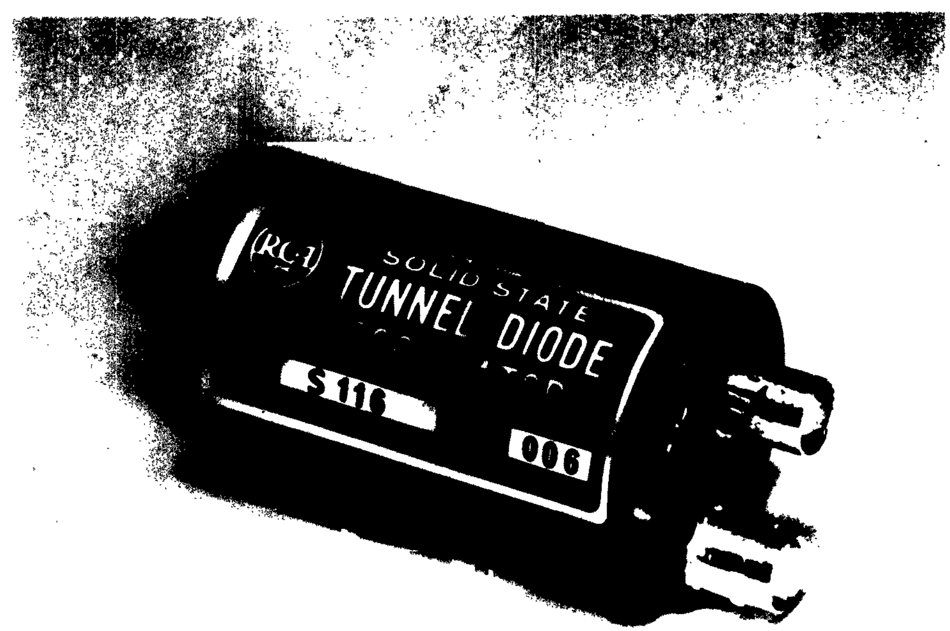

FIG. 39. PHOTOGRAPH OF DEVELOPMENTAL MODEL TUNNEL DIODE OSCILLATOR

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C. TRANSISTOR-OSCILLATOR-MULTIPLIERS

1. Introduction and General Discussion

In August of 1964 work was started on the development of a transistor-oscillator frequency-multiplier combination to provide the higher power needed for the ruggedized BRL sonde units. A few months later it was agreed that the last three developmental models of the standard radiosondes would also be of this type due to the difficulty in compensating the tunnel-diode units and to the promising preliminary results on the transistor units.

The original plan was to use a transistor-oscillator followed by a varactor frequency quadrupler. However, early in the program the use of a single transistor simultaneously as an oscillator and as a frequency quadrupler was found to be feasible and effort was concentrated on this approach because of its adaptability to low production costs. In the remainder of this section a general discussion of transistor-oscillator-multipliers will be given. The following section 2 will present the results on standard radiosonde units while section 3 will give results on the ruggedized BRL units.

The use of a transistor as a frequency multiplier was suggested several years ago[2] and several papers have appeared in the literature[3,4]. With the advent of transistors giving several watts of power at 500 Mc, such as the type 2N3375 overlay transistor, the use of a transistor as an amplifier-multiplier or oscillator multiplier to give appreciable power at microwave frequencies became possible. In the work described, a similar transistor, type 2N3553, was used as an oscillator-quadrupler to provide 100 to 500 mw of power at 1660 to 1680 Mc or at 1750 Mc. The 2N3553 transistor is a less expensive version of the 2N3375, employing the same overlay type semiconductor pellet but having a TO5 type package.

The power source using this transistor may be frequency modulated and is particularly adapted to radiosonde and similar applications.

In the oscillator-quadrupler the transistor was employed in a conventional oscillator circuit. In addition a second harmonic idler circuit and a fourth harmonic output circuit were connected between the collector and base of the transistor. The collector-base junction of the transistor thus acts as a voltage variable capacitance to give frequency quadrupling in the same manner as a varactor.

The circuit diagram of an oscillator-quadrupler is shown in Figure 40. The oscillator circuit, contained in the dotted lines, employs the transistor in a grounded base configuration and is basically a Colpitts type circuit. The emitter feedback is through the transistor collector-emitter capacitance. The inductances of the collector-base resonant circuits are shorted lengths of strip transmission lines. The quadrupler portion of the circuit consists of a second harmonic idler circuit and a fourth harmonic output circuit connected between base and collector. In the design of the three resonant circuits, fundamental, second harmonic idler and output circuit, it is necessary to consider the response of each circuit at all three frequencies. It is particularly important that the fundamental and second harmonic circuits have a high impedance at the output frequency. It is also desirable that the second and fourth harmonic circuits have a high impedance at the fundamental frequency, especially if single control tuning is required.

A photograph of a typical oscillator-quadrupler is shown in Figure 41. From top to bottom are seen the 420 Mc fundamental stripline circuit, the 840 Mc idler and the 1680 Mc output circuit. Figure 42 is a bottom view of the circuit showing the biasing circuit and a voltage regulator transistor circuit. Curves

TRANSISTOR OSCILLATOR – QUADRUPLER
CIRCUIT DIAGRAM

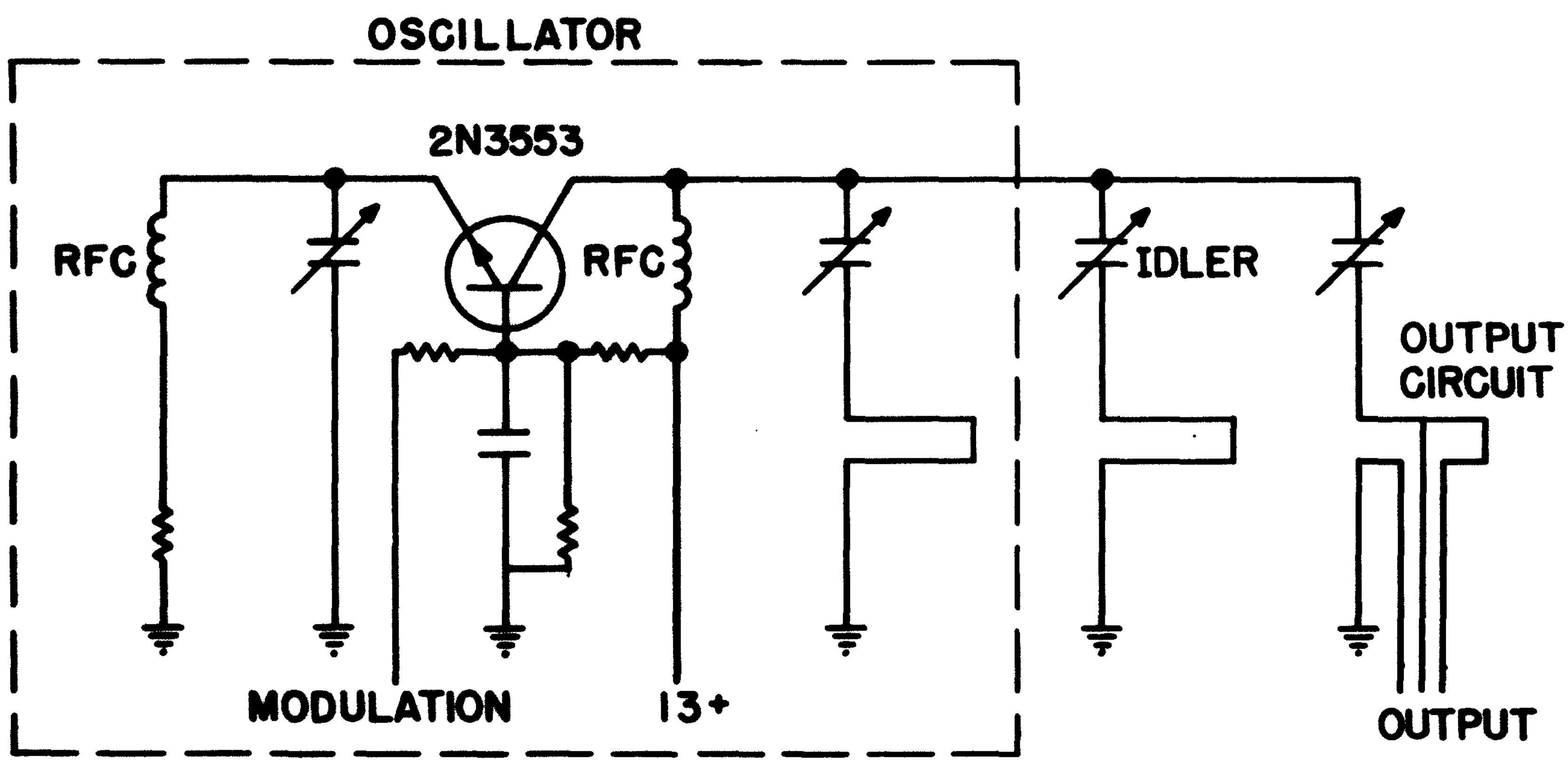

FIG. 40

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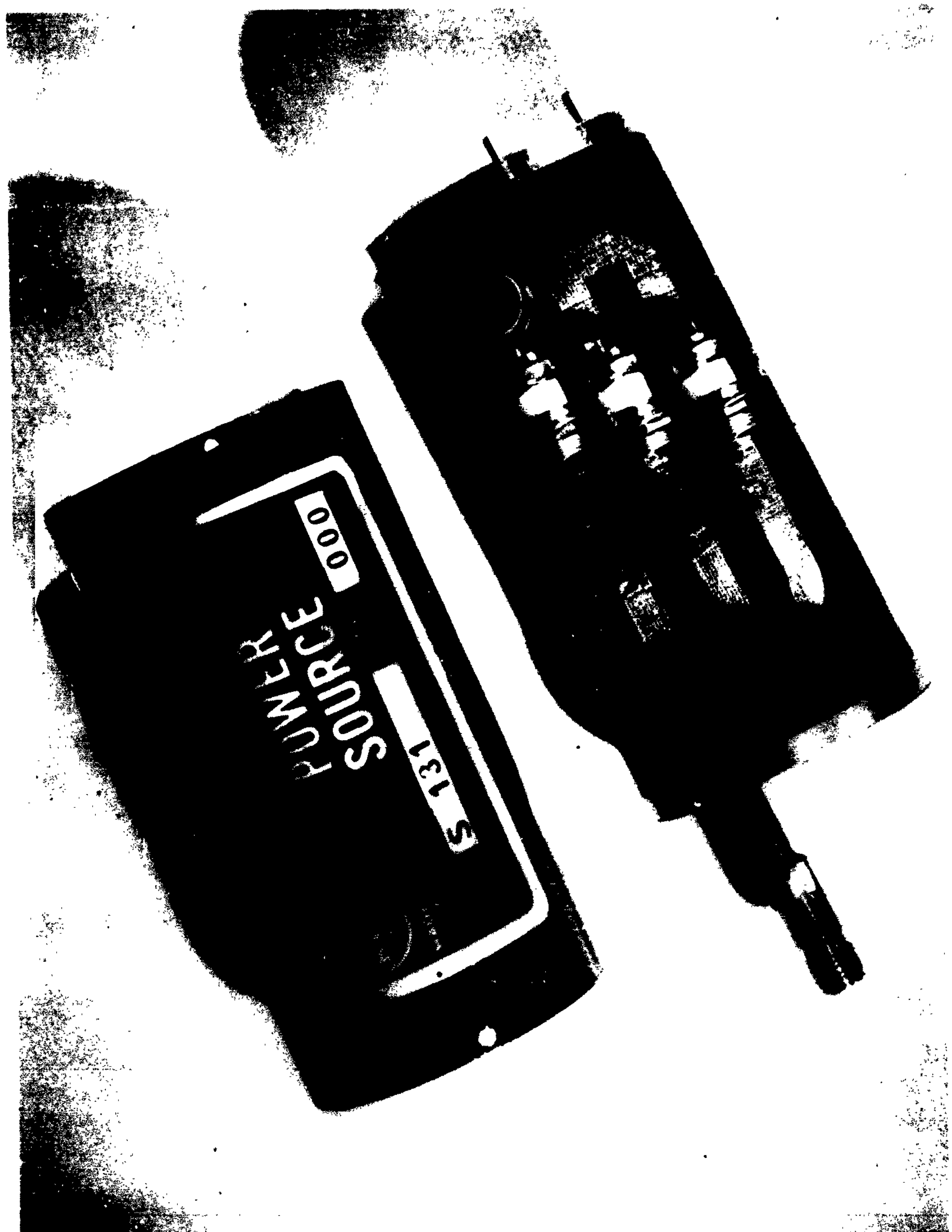

TRANSISTOR OSCILLATOR-QUADRUPLER
FIG. 41

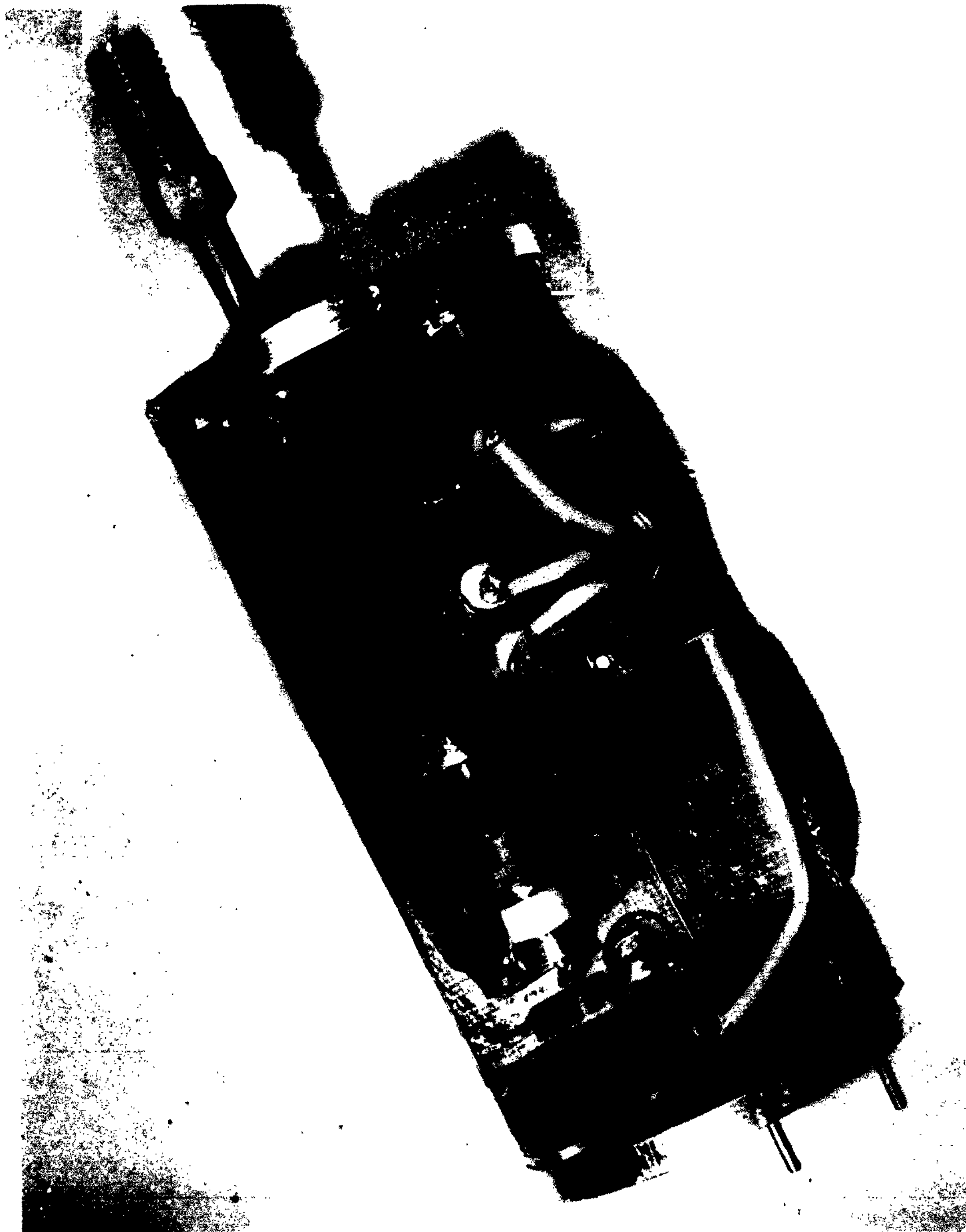

FIG. 42 PHOTOGRAPH BOTTOM VIEW OF TOM

of power output, efficiency and frequency versus supply voltage are shown at the top of Figure 43. A simple transistor voltage regulator circuit to reduce the variation of power output and frequency with changes in supply voltage will be described in the following section. Performance of the unit with such a voltage regulator is shown at the bottom of Figure 43. Performance of the unit with such a voltage regulator is shown at the bottom of Figure 43.

Frequency modulation is accomplished by applying voltage to the base bias resistor. Figure 44 shows the FM spectrums for a deviation of 125 kc at serveral sine wave modulating frequencies. Deviations up to several megacycles are possible. The power source may be mechanically tuned over a range of 50 Mc with less than 1 db power variation by tuning the fundamental circuit capacitor. Through the replacement of the capacitor by a varactor electronic tuning can be performed.

Figure 45 shows waveforms of an oscillator-quadrupler taken with a sampling scope. The left hand waveform is the voltage across the inductance of the fundamental circuit. It will be noted that it contains a third harmonic component. There is no circuit provided for the third harmonic so that this component "sees" a high impedance and a fairly high voltage is present. The center picture shows the output voltage across the load. Although the fundamental component can be discerned in the pattern, its amplitude is quite small. The right hand figure shows the emitter current of the transistor. This waveform may not be too accurate since the sampling resistor put in the emitter circuit disturbed the operation of the unit reducing the output power to about two thirds of its original value.

A brief explanation of the nomenclature used in this and subsequent

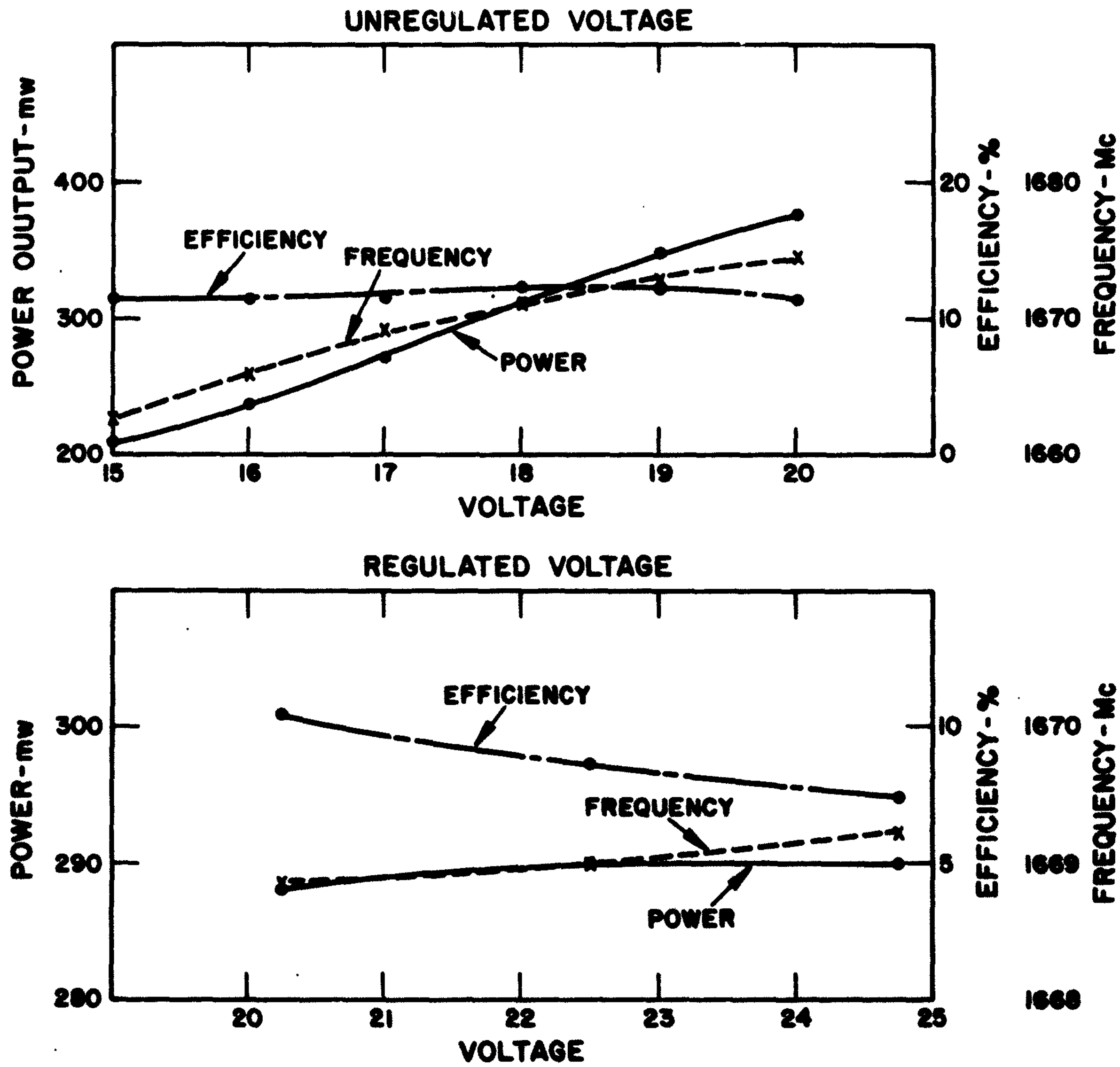

FIG. 43 RCA TRANSISTOR-OSCILLATOR-MULTIPLIER PERFORMANCE CURVES S-131 SERIAL NO. 002

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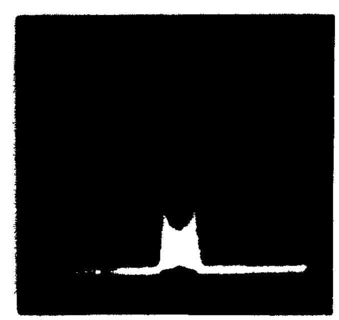
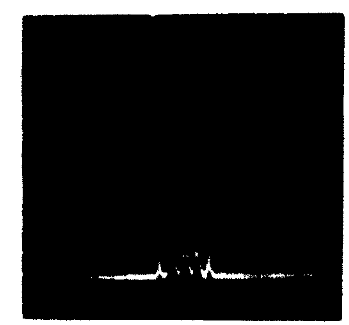
MODULATING VOLTAGE 1 VRMS

HORIZONTAL SCALE 200 kc/cm

F_s = 500 cps



F_s = 5000 cps



F_s = 100,000 cps

SPECTRUM OF FREQUENCY MODULATED TRANSISTOR
OSCILLATOR - QUADRUPLER
FIG. 44

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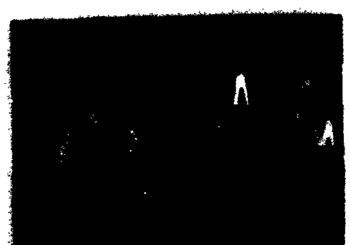
OUTPUT FREQUENCY 1690 Mc
OUTPUT POWER 200 mw
HORIZONTAL SCALE 1 NANOSECOND / cm



VOLTAGE ACROSS INDUCTANCE OF FUNDAMENTAL CIRCUIT

OUTPUT VOLTAGE

EMITTER CURRENT

WAVEFORMS OF TRANSISTOR OSCILLATOR-QUADRUPLER
FIG. 45

sub-sections of this report is in order. We have used "Transistor-Oscillator Multiplier" or "TOM" as a generic name for solid state power sources employing a single transistor simultaneously as an oscillator and as a frequency-multiplier. However the units delivered under this contract intended for standard radiosonde applications were also called "Solid State Harmonic Generators" while those intended for gun-probe sonde application were called "Solid State Oscillators". These are contractual names which came about because it was not known at the time of contract modification that the units would be TOMs rather than transistor-oscillator varactor-multipliers and also because of the desire to distinguish between units for standard radiosondes and gun-probe sondes in contractual correspondence. In any case all units discussed in this and following subsections of section IV-C were TOMs or more specifically Transistor-Oscillator-Quadruplers.

2. Standard Radiosonde Units

In addition to the requirements of around 250 milliwatts of power output at reasonable efficiency and capability for modulation, a major consideration in TOMs for standard radiosonde applications is frequency stability. Frequency changes in TOMs rise from three major causes; changes in output load, changes in supply voltage and changes in ambient temperature. In all units tested the frequency change due to output load changes was within tolerable limits; the pulling figure for all possible phases of a 1.5 VSWR of the output load was less than 2 Mc. The use of a voltage regulator to reduce frequency changes due to supply voltage changes was briefly described in the previous subsection and details of the circuit will be given below. Thus in the final few weeks of the contract during which the final three developmental model "Solid State Harmonic Generators" were to be fabricated, the major remaining problem was that of frequency stability under varying

ambient temperatures. Due to limited time and effort remaining on the program it was decided to concentrate on the ambient temperature problem and to eliminate effort planned toward a reduction in package size. It should be pointed out that the ambient temperature compensation and reduction in package size considerations are not in conflict and that with limited additional work an appreciable reduction in package size of the temperature compensated units could be realized.

Ambient Temperature Compensation - Tests on uncompensated units showed frequency changes of 25 to 50 Mc occurred when the ambient temperature was varied from -50°C to +75°C. The use of negative temperature coefficient capacitors in the emitter circuit of the transistor oscillator reduced this variation to about 7 Mc. However, the capacitance values of the negative coefficient capacitors were critical and there were large variations of transistor current and power output as the ambient temperature varied. A combination of a negative temperature coefficient capacitor in the emitter circuit and a positive coefficient resistor in the base bias circuit reduced the frequency change to 4 Mc or less and resulted in much less change in current and power output over the ambient temperature range. The three developmental model harmonic generators delivered incorporated this technique as shown in the schematic diagram which follows. Further improvement is undoubtedly possible as time limitations required that the temperature compensation be done with a minimum effort.

Voltage Regulation - The final three units also incorporated a simple transistor voltage regulator, designed to decrease the frequency changes due to ± 10% supply voltage changes, from about 10 Mc to 1 Mc. The schematic of the voltage regulator is shown in Figure 46.

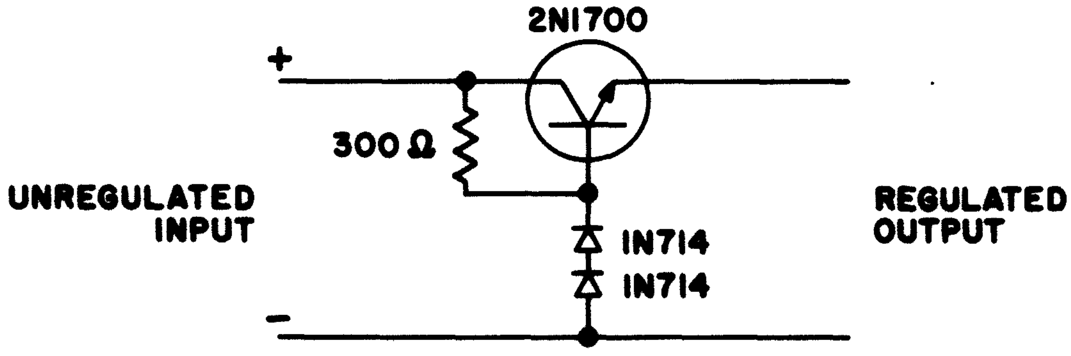


FIG. 46 TRANSISTOR VOLTAGE REGULATOR

Final Developmental Models - A photograph of the S131 TOM delivered as final development model Solid State Harmonic Generators (item 3c) is shown in Figure 47 while Figure 48 shows a view of the circuit board assembly. This particular unit, Serial 004, has extra stripline filter sections in the output circuit. These were intended to reduce spurious output but there was insufficient time to optimize the filter and the improvement was negligible. The remaining two units did not have the extra filter sections but were as shown in the fabrication drawings which follow.

Test data on the three units is tabulated below while curves of performance over the ambient temperature range are given for the three units in Figures 49, 50 and 51.

Test Data for S131 Solid State Harmonic Generators

Serial No.		004	005	006
Modulation voltage for ±150 kc frequency deviation at repetition rates 50 to 500 cps		±0.7 volts	±0.6 volts	±0.8 volts
Pulling Figure 1.5 VSWR		1.5 Mc	1.0 Mc	2.0 Mc
Power output at frequency	1660	190 mw	197 mw	205 mw
	1671	210 mw		
	1692		280 mw	310 mw
	1700	160 mw	276 mw	310 mw

Fabrication Data - A parts list for the S131 TOM units made for the standard radiosonde applications follows. Figure 52 shows the schematic circuit diagram. Figures 53 and 54 show assembly views giving the location of the components. The three units of this type construction were originally fabricated as identical as possible.

FIG. 47 PHOTOGRAPH OF S-131 TOM

FIG. 48 PHOTOGRAPH OF CIRCUIT BOARD ASSEMBLY S-131

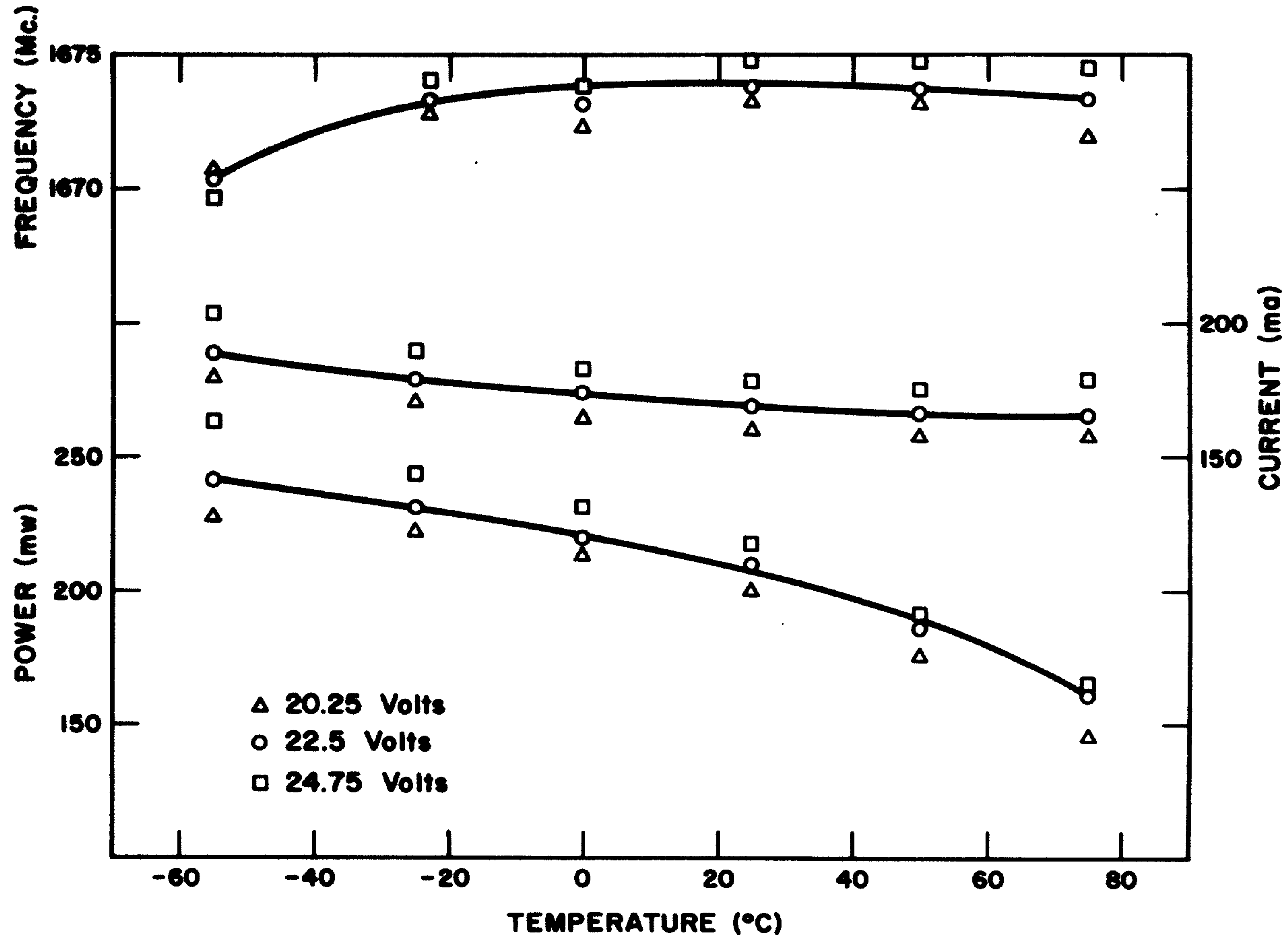


FIG. 49 PERFORMANCE vs AMBIENT TEMPERATURE
S-131 TOM SERIAL NO. 004

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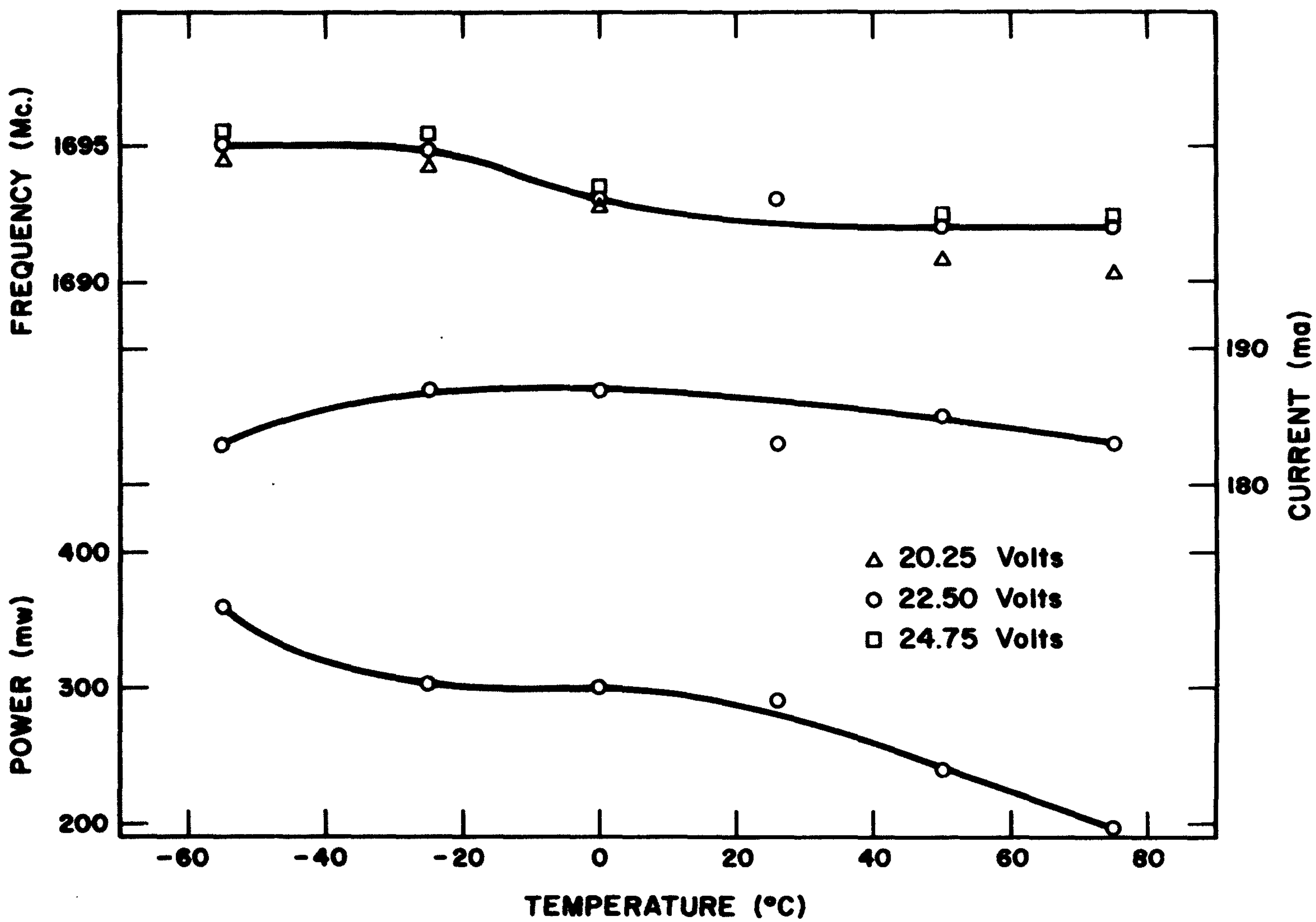

FIG. 50 PERFORMANCE vs AMBIENT TEMPERATURE
S-131 TOM SERIAL NO. 005

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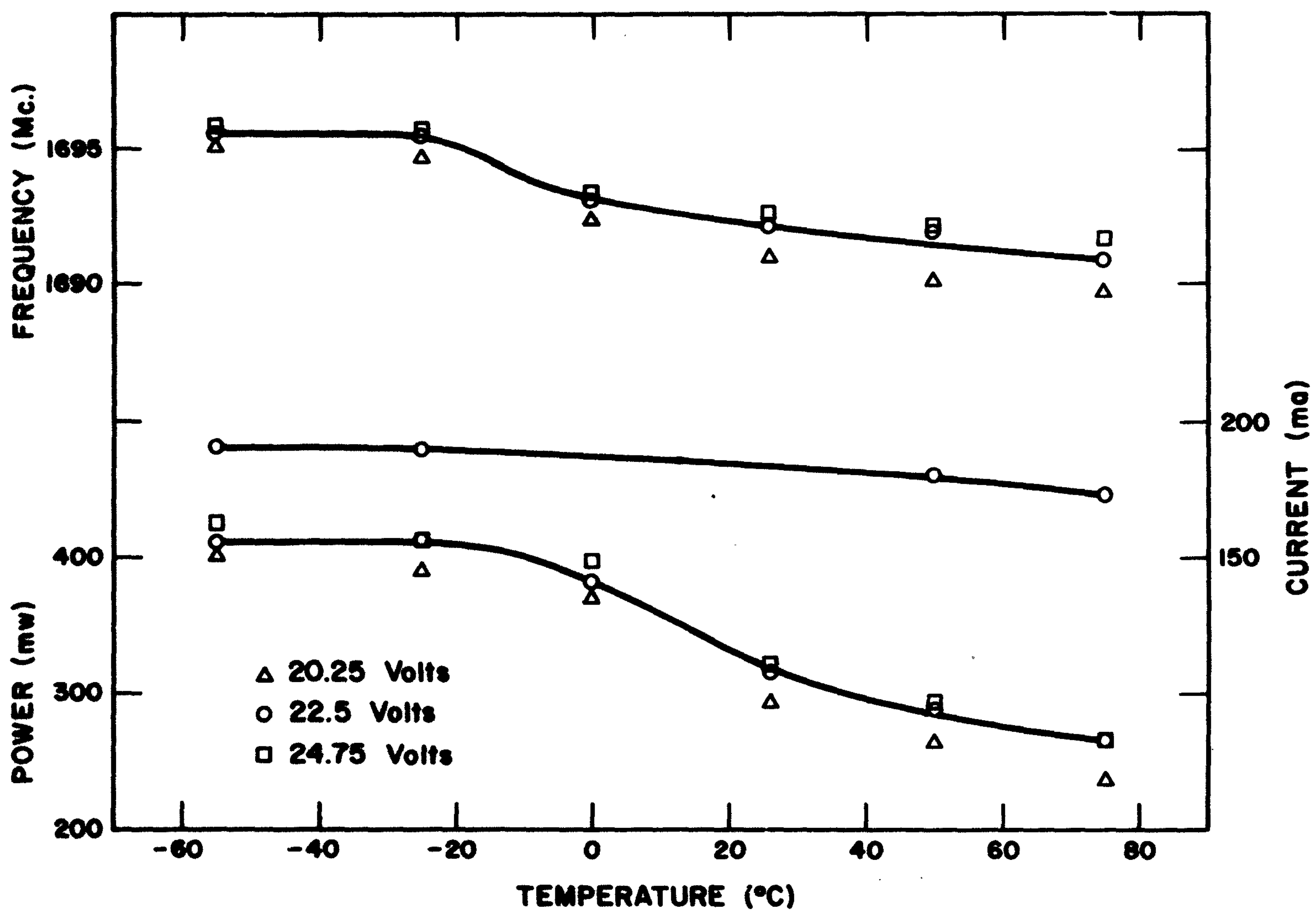

FIG. 51 PEFORMANCE vs AMBIENT TEMPERATURE
S-131 TOM SERIAL NO. 006

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LIST OF COMPONENTS

DESIGNATION	DESCRIPTION	NO. REQ'D.
T_1	RCA 2N3553	1
T_2	RCA 2N1700	1
R_1	1/4 W - 2.7Ω	1
R_2	1/4 W - 200 Ω	1
R_3	T. I. - TM 1/4 820 Ω	1
R_4	1/4 W - 300 Ω	1
R_5	1/4 W - 5100Ω	1
L_1	Ohmite 0.22 μh	1
L_2	5 Turns 0.025" Wire 20 T.P.I. 0.170 I.D.	1
L_3	Fundamental Line-2.5" of 50ohm Strip Transmission Line in 1/16 Teflon Fiberglass Circuit Board 1.725" Diameter	1
L_4	Idler Line-?.1" of 50ohm Strip Transmission Line in 1/16" Teflon Fiberglass Circuit Board 1.063x1.45 Overall	1
L_5	Output Line - Same as L_4	1
C_1	Johanson 4335 1-10 pf	4
C_2	American Lava Leadless T157 200 pf in Parallel with Uniceram 39 pf	1
C_3	American Lava Leadless N2200 6 pf	1
D_1	T.I. IN 714	2

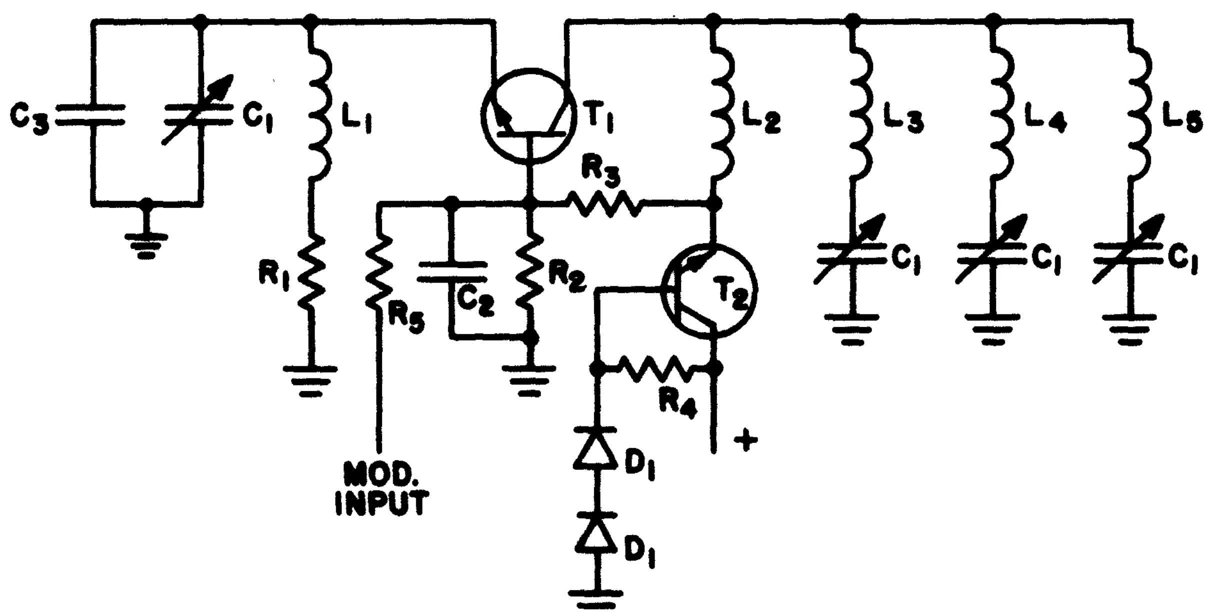

FIG.52 SCHEMATIC DIAGRAM S131

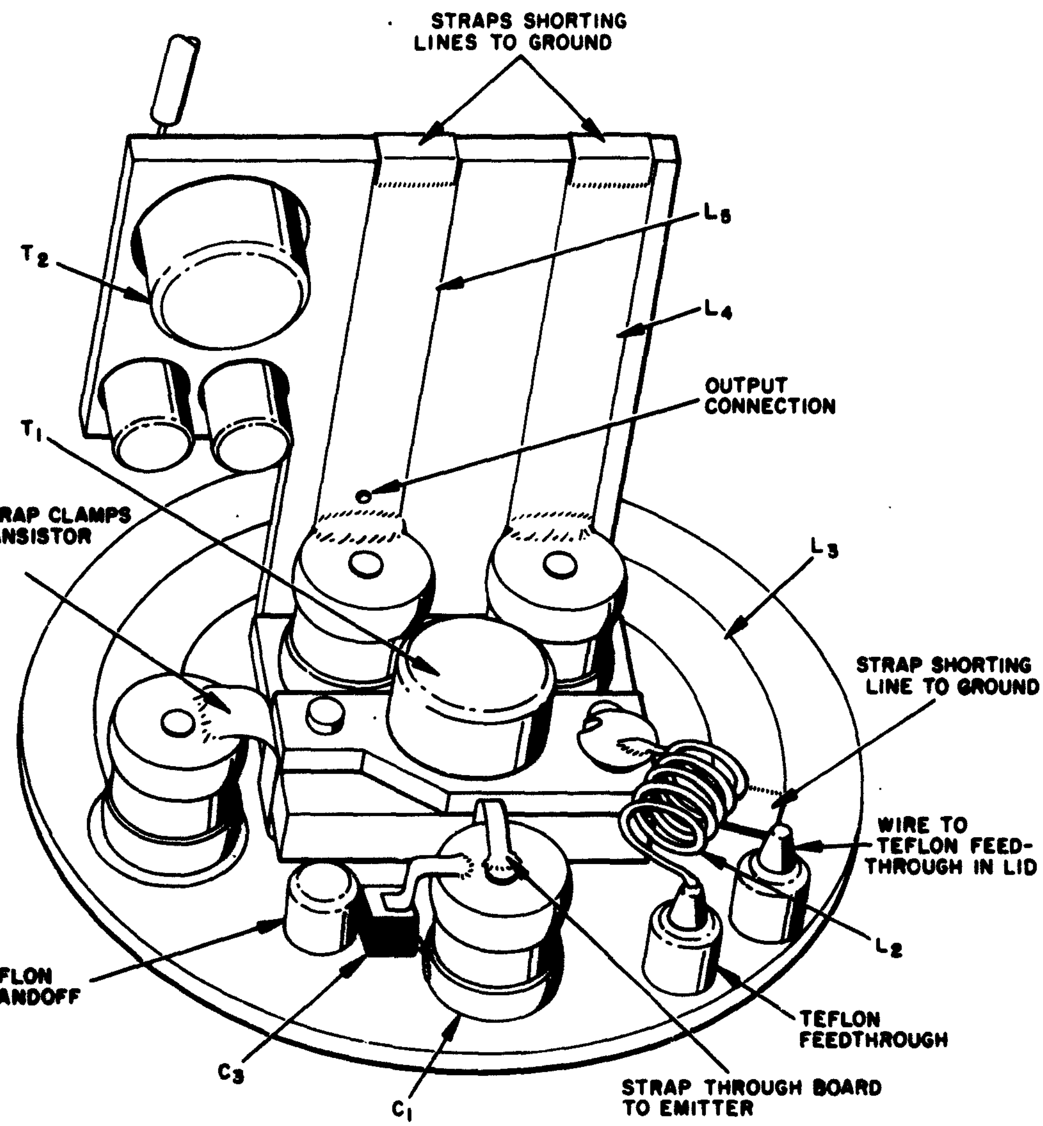

FIG. 53 CIRCUIT ASSEMBLY (FRONT VIEW)

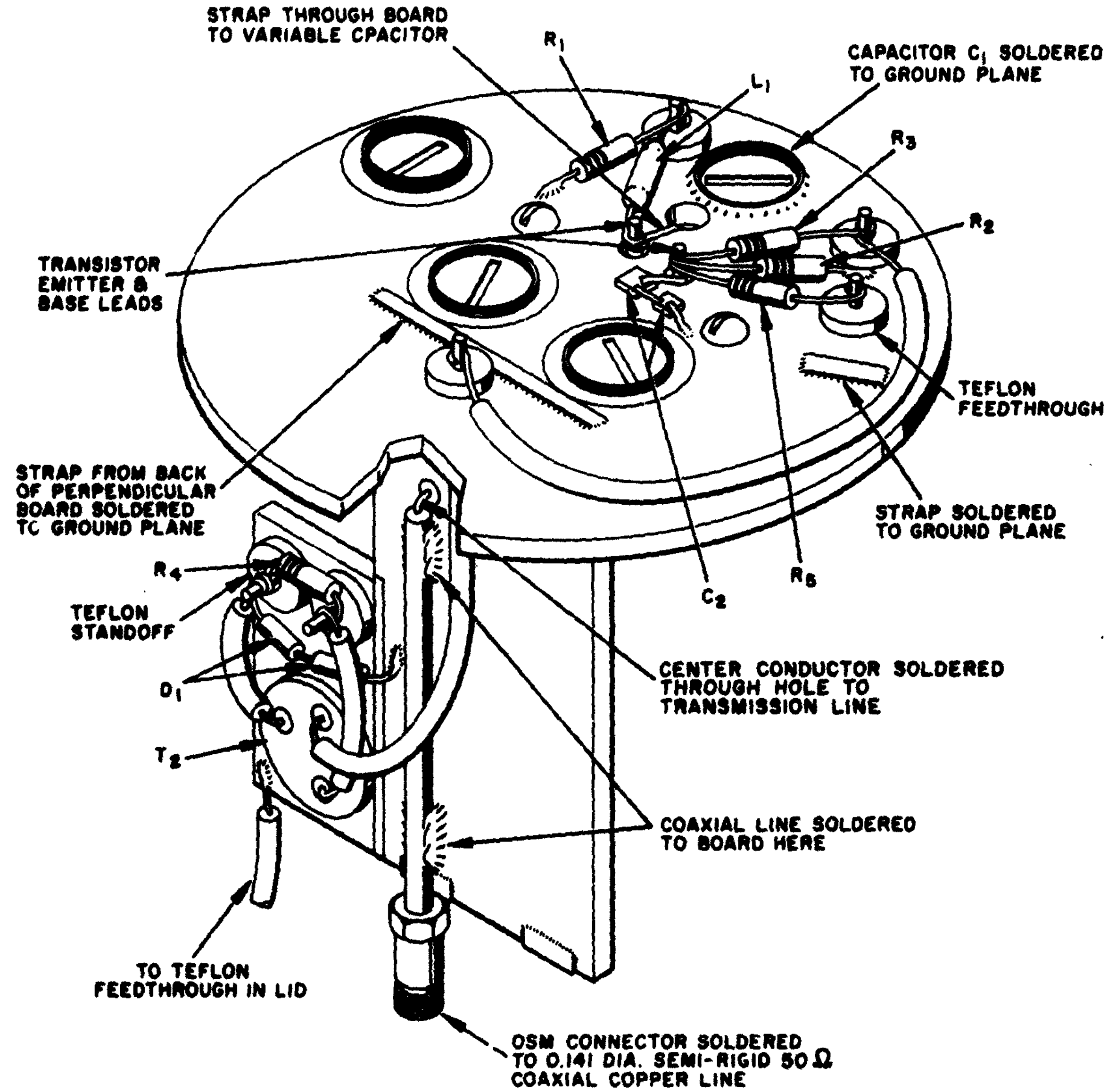

FIG.54 CIRCUIT ASSEMBLY (BACK VIEW)

However, in order to optimize performance minor variations were made primarily in lead dress or the addition of 5 pf shunting capacitors in the emitter or fundamental rf circuit. Since the transistors characteristics are very constant from unit to unit we believe that a mass produced version of optimized design will eliminate any need for such variations.

3. Ruggedized Gun Probe Sonde

The requirements on the TOM for gun probe application were considerably different from those of the standard sondes. The most important characteristics were the capability to withstand 50,000 g acceleration and size. Some of the requirements which could be relaxed were frequency stability, thus making it unnecessary to temperature compensate or to include a voltage regulator in the sonde and tuning range requirement. Photographs showing internal details of the unit are shown in Figures 55 and 56.

Packaging - Space requirements limited the size of the unit to a cylinder 1.2" in diameter. In addition space for leads to the unit had to be provided in a chord across the side of the cylinder. This resulted in a D-shaped package as shown in Figure 57. The output is taken through a length of 0.085" semirigid coaxial line which can be bent along the chord to an antenna located in the sonde package a few inches from the TOM.

Acceleration - Preliminary tests on the transistors used in the TOMs indicated a probability of meeting the 50,000 g acceleration requirement although further tests are needed to determine whether pretesting of each transistor is needed to insure reliability. Effort was therefore concentrated on the ruggedized design of the TOM unit and the use of potting to increase the capability to withstand high

FIG. 55 BOTTOM VIEW OF CIRCUIT BOARD ASSEMBLY S-143 TOM

FIG. 56 TOP VIEW OF CIRCUIT BOARD ASSEMBLY S-143 TOM

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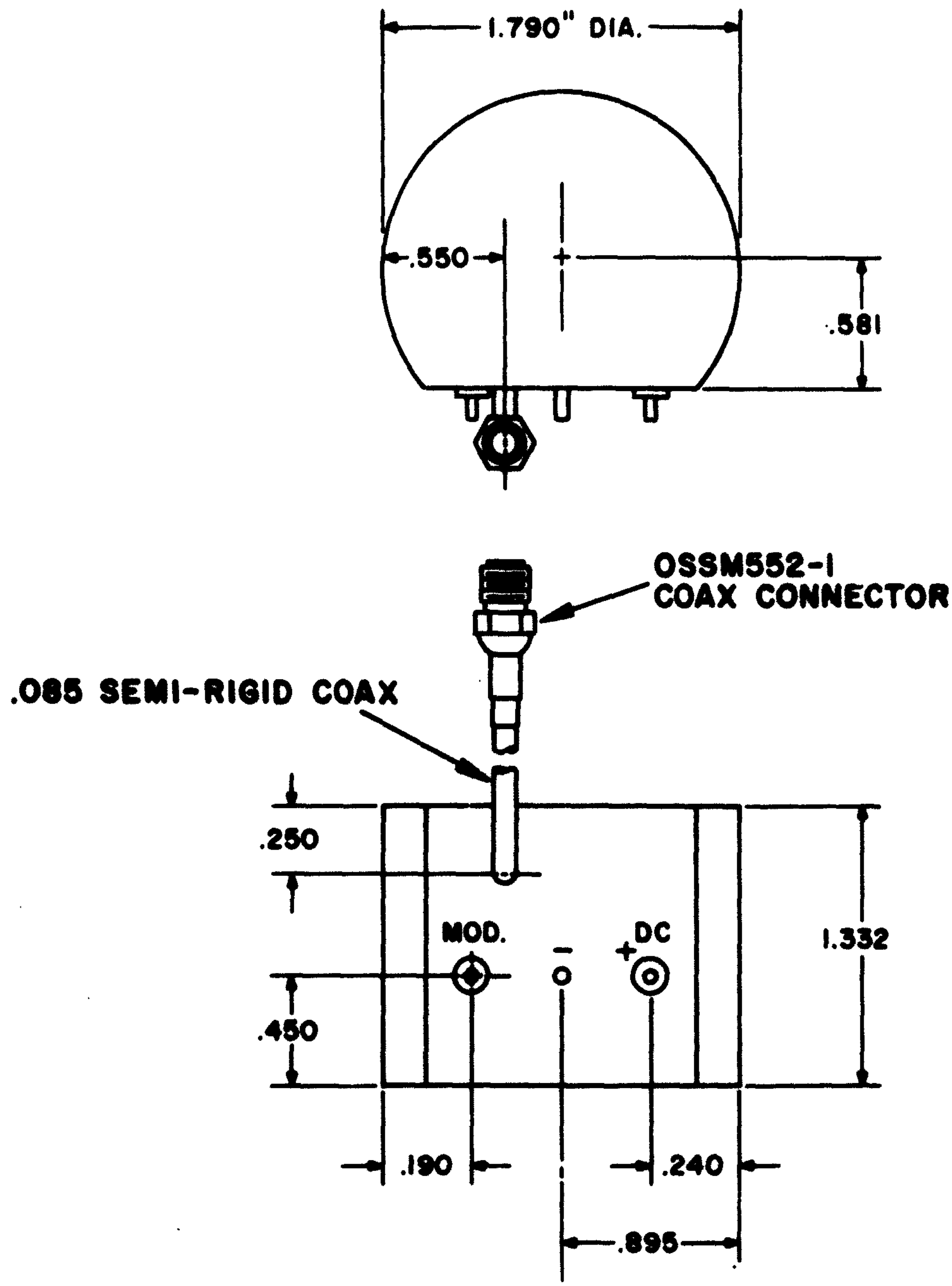

FIG. 57 S-143 TOM OUTLINE

acceleration. The initial attempt at potting was to use Emerson and Cuming Stycast 1090 SI and to completely pot both the top and bottom space around the circuit board assembly. This resulted in a reduction of about 5 times in the power output which could not be regained by retuning the unit. In order to reduce this effect the next unit was completely potted on the underside of the circuit board (except for space taken up by four ¼" diameter lengths of plastic tubing which permitted the Johanson capacitors to be tuned after potting) but the potting on the top side was limited to a quarter inch radial dimension around the outside of the circular portion of the D. Thus the center portion and the area along the straight edge of the D remained unpotted. This resulted in satisfactory operation and was used on the remaining units. At this writing one S-143 TOM has been acceleration tested at the Ballistic Research Laboratories, Aberdeen Proving Ground. After an acceleration of 15,000 g the unit operated satisfactorily with little change in characteristics. The unit was refired at 37,000 g and failed due to failure of a lead in the transistor. Previously a limited number of 2N3553 transistors had tested satisfactorily at 50,000 g. Further tests will be required to determine whether an improvement in the transistor or pretesting of transistors before putting them in TOM units will be required to give adequate reliability.

Electrical Test Data - A total of five Solid State Oscillators (item 3e) were delivered on the contract. The first two were breadboard units not packaged in the final configuration. Data on the final two ruggedized units in the final package is as follows:

S-143 Solid State Oscillators s/n 002 and 005

	002		005	
Vin	20V	15V	19V	15V
Iin	155 ma	115 ma	155 ma	120 ma
Pin	3.1w	1.7w	2.95w	1.8w
Pout	250 mw	118 mw	250 mw	120 mw
Eff	8.2%	6.9%	8.5%	6.7%
Fo	1745 mc	1740 mc	1765 mc	1760 mc

	002	005
Pulling figure at 1.5:1 VSWR	1.0 mc	0.8 Mc

Frequency Modulation at 25 Kc, 10 Kc, 500 cps, 50 cps.

002: 640 Kc Peak to Peak for 1 Volt RMS

005: 720 Kc Peak to Peak for 1 Volt RMS

Frequency and Power Output vs. Time

Time	Freq. s/n 002	Power s/n 002	Freq. s/n 005	Power s/n 005
Turn on	1736 mc	118 mw	1762 mc	120 mw
1 minute	1735	118	1760	123
2 minutes	1734.5	118	1759.5	123
3 minutes	1734	118	1759	123
4 minutes	1733.5	120	1758.5	121
5 minutes	1733	120	1758	121
10 minutes	1732	118	1757	116
15 minutes	1731	116	1756	116

Fabrication Data - A parts list for the S-143 TOM units for the gun probe sonde application follows. A schematic circuit diagram is shown in Fugure 58. Figures 59 and 60 show assembly views giving the location of the components.

Parts List

S-143 Solid State Oscillator

Q	RCA 2N3553 transistor
R_1	2.7 ohms ¼ watt resistor
R_2	200 ohms ½ watt resistor
R_3	1000 ohms ½ watt resistor
R_4	5100 ohms ¼ watt resistor
C_1, C_2, C_3, C_4	1-10 pf capacitors Johanson 4904A
C_5	5 pf capacitor JFD Uniceram
C_6	200 pf capacitor, leadless disc
C_7	39 pf capacitor, JFD Uniceram
C_8	68 pf capacitor, leadless disc
L_1	2.36" length of shorted 50 Ω line printed on 1/16" teflon-fiberglass stripline
L_2	1.10" length of shorted 50 Ω line printed on 1/16" teflon-fiberglass stripline
L_3	1.10" length of shorted 50 Ω line printed on 1/16" teflon-fiberglass stripline
L_4	5 turns #22 bus wire
L_5	Ohmite 2-460 RFC
E_1	#1-72 Machine screw
E_2, E_3, E_4	Cambion 4176-3 teflon feed thru
E_5	Cambion 4029-3 teflon standoff
RG-1	0.085" semirigid transmission line
SO-1	Omni Spectra OSSM coaxial connector

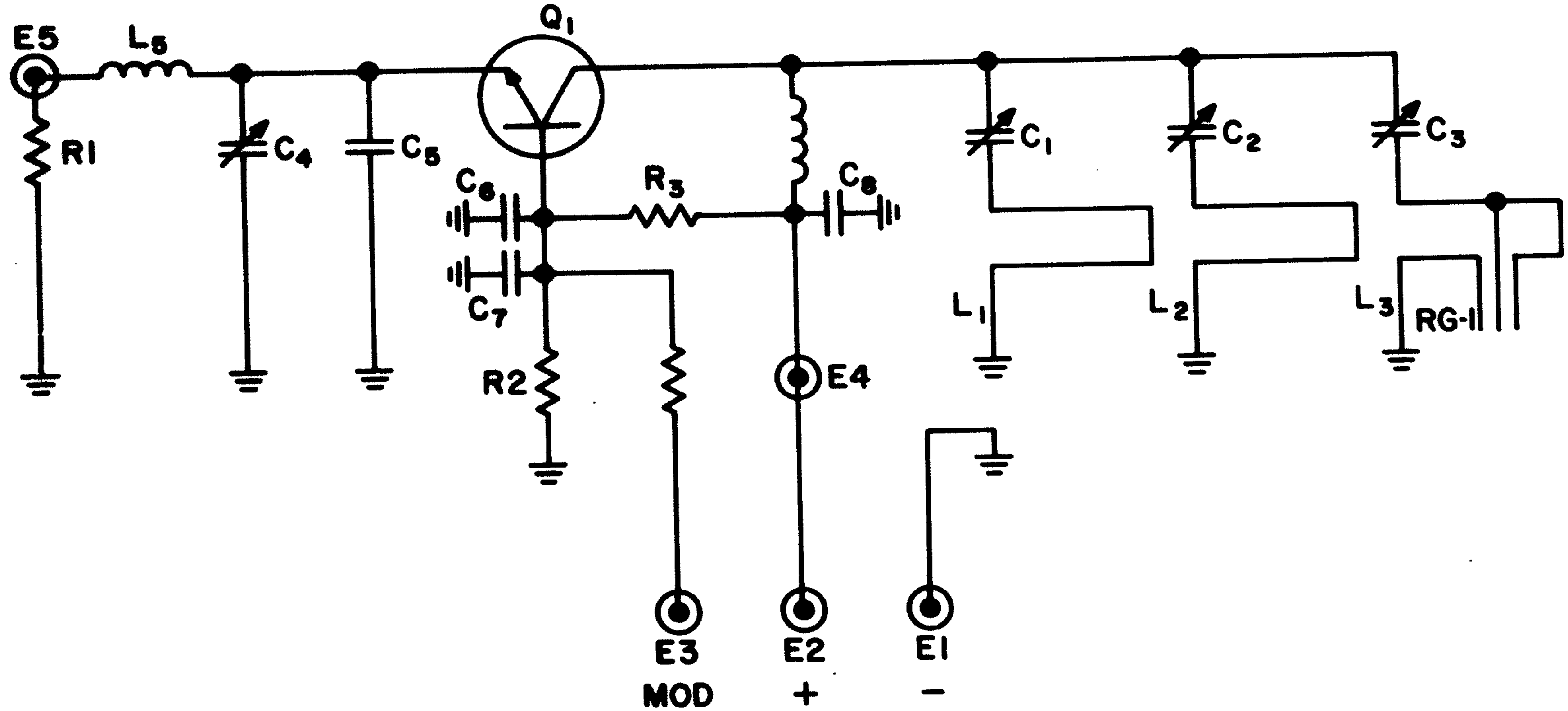

FIG. 58 SCHEMATIC DIAGRAM S-143 SOLID STATE OSCILLATOR

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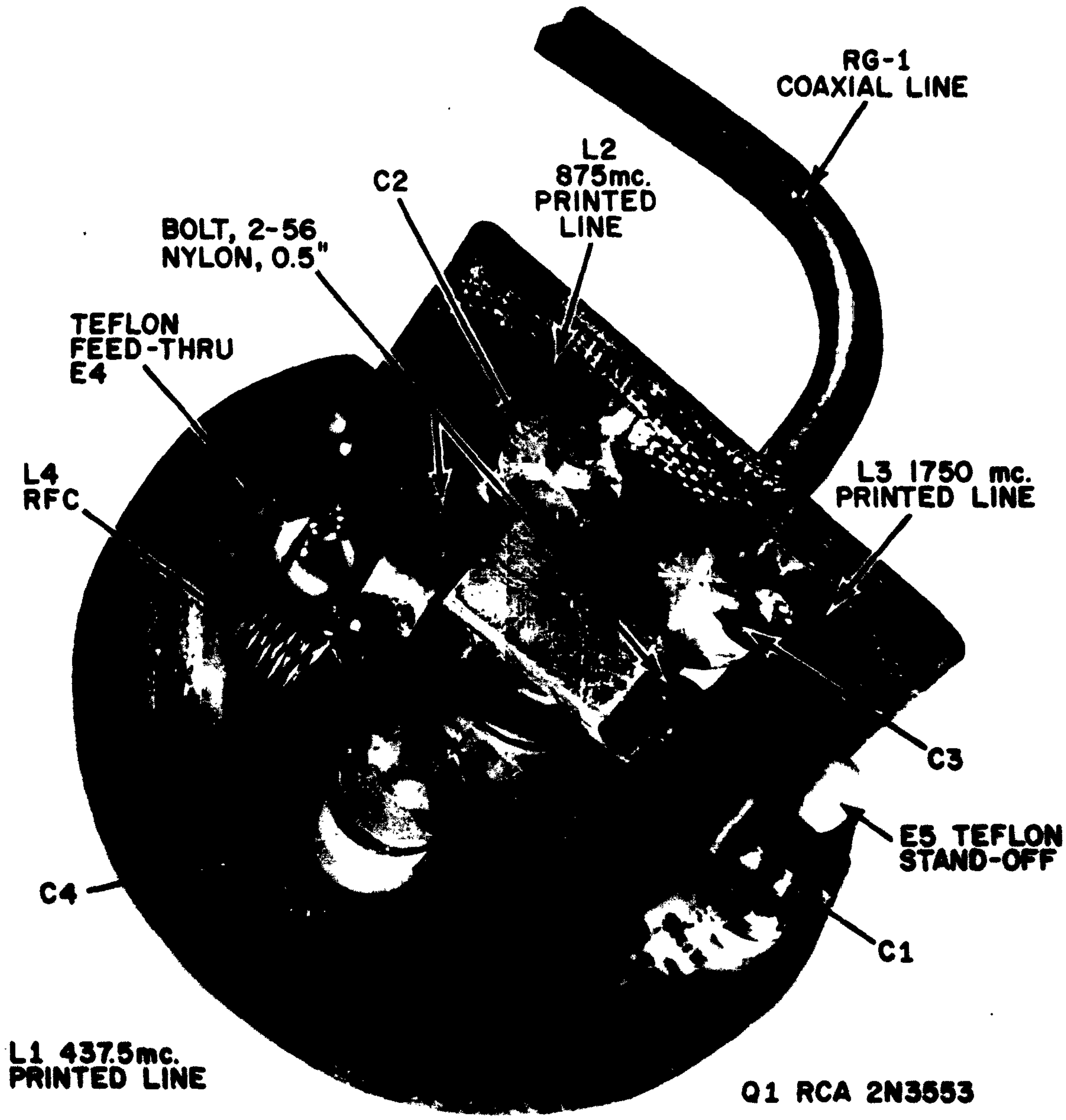

FIG. 59 TOP VIEW MODEL S-143 SOLID-STATE OSCILLATOR

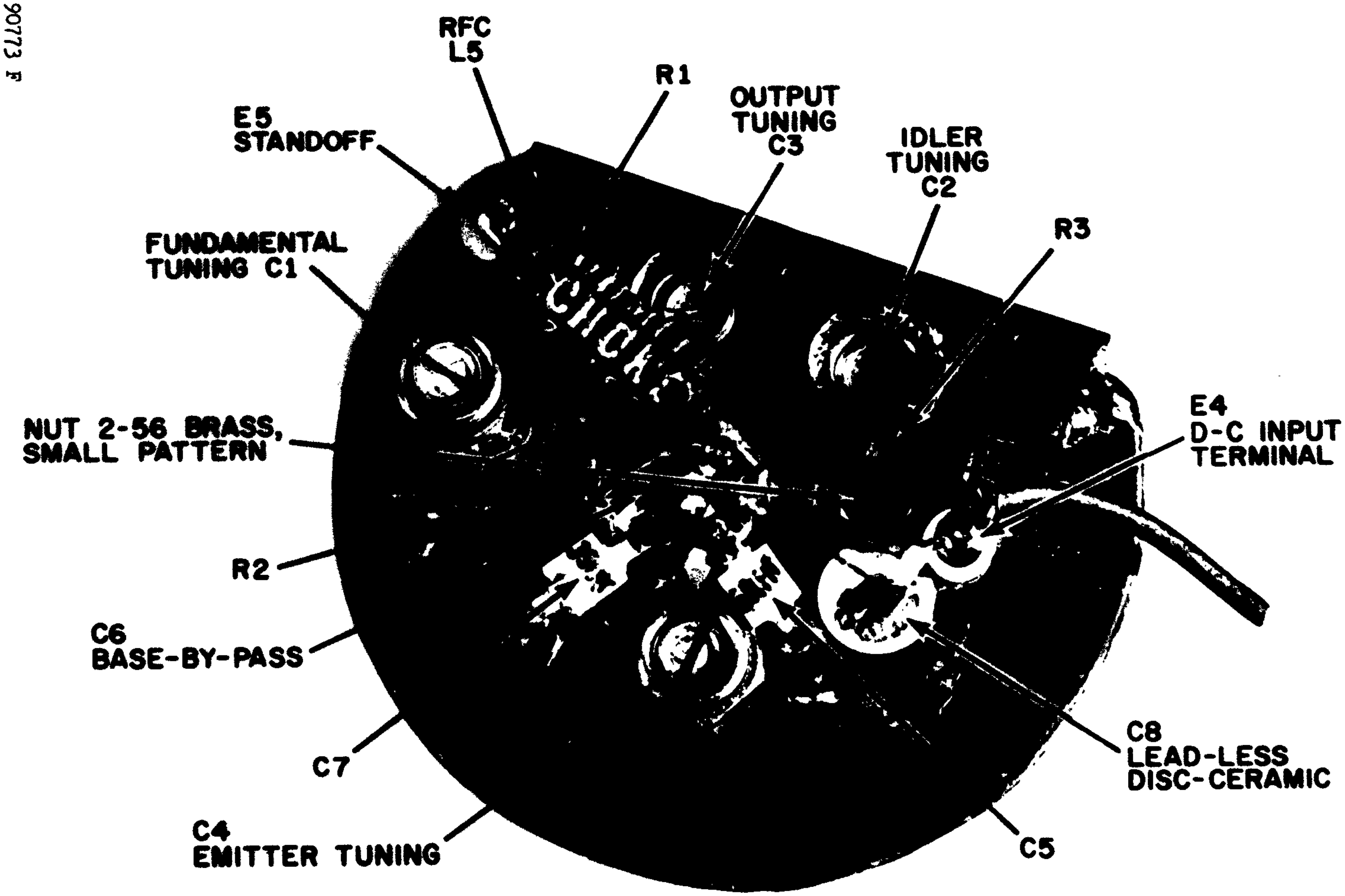

FIG. 60 BOTTOM VIEW MODEL S-143 SOLID STATE OSCILLATOR

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SECTION V

OVERALL CONCLUSIONS

A. TUNNEL-DIODE OSCILLATORS

Gallium-Arsenide tunnel-diodes mounted in a low inductance package were fabricated having 600 ma peak current and resistive cutoff frequencies of 6 to 10 Gc. These diodes were successfully operated in oscillators giving 20 to 30 milliwatts output power over a 1660 to 1700 Mc frequency range.

The very low impedance (one to two ohms) of the oscillator circuits necessary for operation of the high current diodes at microwave frequencies resulted in low Q circuits. This caused difficulty with respect to the frequency stability requirements. A transistor current regulator was designed to enable the oscillators to meet the ± 2 Mc maximum frequency change for a $\pm 10\%$ variation of supply voltage.

The pulling figures of the order 100 Mc can be reduced through the use of a load isolator. However, considerable engineering effort would be required to reduce the change in frequency due to ambient temperature to the objective value of ± 2 Mc for temperatures from $-55^{o}C$ to $+75^{o}C$. It is our opinion that the complexity of a system for temperature compensation would add to the unit cost to such an extent as to prohibit the use of tunnel-diode oscillators for radiosonde and similar low-cost applications.

B. TRANSISTOR-OSCILLATOR-MULTIPLIERS

1. Gun Probe Sonde

A transistor-oscillator-quadrupler was developed using the RCA 2N3553 transistor. Typical results were 250 mw power output at a frequency of 1750 Mc for 20 volts input at an efficiency greater than 8%. The units could also be

operated at 15 volts input giving over 100 mw at just under 7% efficiency (this is an alternate operating point considered by BRL to reduce thermal dissipation problems). The units were packaged in a size compatible with the gun probe requirement. Other characteristics were pulling figure - about 1 Mc for 1.5 VSWR and frequency modulation characteristic - about 700 kc frequency deviation for 1 volt RMS modulating voltage.

One unit was acceleration tested by BRL and two additional units were delivered for test. The unit tested operated satisfactorily after 15,000 g acceleration but failed due to the failure of a lead in the transistor at 37,000 g. A small number of transistors satisfactorily passed a 50,000 g test. Thus further tests on both transistors and TOM units are needed to determine acceleration characteristics. It may be necessary to either improve the transistor or to acceleration pretest the transistors before putting them in TOM units in order to insure reliability under acceleration conditions.

2. Standard Radiosonde

The S131 transistor-oscillator-quadruplers tested and delivered on the contract demonstrate the feasibility of meeting the radiosonde specifications. Typical results are power output in excess of 250 milliwatts at 1680 Mc at 6 to 7% overall efficiency including the voltage drop in the transistor regulator. Although the power output dropped to about 200 mw at the lower end of the 1660-1700 Mc tuning range in the temperature compensated units, this is not a serious problem but is due to lack of time to simultaneously optimize the temperature compensation and power versus tuning characteristics. The units easily met the ±2 Mc maximum frequency change for ±10% supply voltage. Frequency changes of less than

4 Mc were obtained over the -55°C to +75°C ambient temperature range. Although the frequency change was not centered at ±2 Mc from the room temperature value, we are confident that this can be done with small additional effort. (The TOM development and temperature compensation was done during the final four months of the contract and considerable improvement can be expected through optimization of the present design with little additional effort.) The pulling figures of the units at 1.5 VSWR were 2 Mc or less. Frequency modulation was readily accomplished by applying a small voltage to the base of the transistor.

SECTION VI

RECOMMENDATIONS

The transistor-oscillator-multipliers developed on this program have demonstrated the feasibility of meeting present radiosonde specifications. RCA therefore recommends that the following tasks be considered for future activity in this area:

1. Product design of a low cost unit meeting present radiosonde specifications. Such a unit would use printed stripline circuits and would be designed to minimize the number of lumped components.

2. A development program to further improve frequency stability and other performance characteristics to meet advanced system specifications and to further reduce production costs. This program would include hybrid or fully integrated circuit techniques.

3. Further development of ruggedized gun probe units to improve performance and assure reliability at accelerations up to 50,000 g.

SECTION VII

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Robert D. Gold	-	Engineering Leader	282
Chester Gurwacz	-	Engineer	61
Han C. Lee	-	Engineer	92
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Arthur Solomen	-	Engineering Leader	26

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13. ABSTRACT

A. TUNNEL-DIODE OSCILLATORS

Gallium-arsenide tunnel diodes having 600-ma peak current and resistive cutoff frequencies of 6 to 10 Gc were developed. The diodes were fabricated in a low-inductance package permitting operation at L-band at power outputs up to 30 mw.

Low-impedance oscillator circuits were designed which gave power outputs of 20 to 30 mw over the required 1660-to 1700-Mc tuning range. A transistor current regulator circuit was developed which permitted operation of the oscillators with $\pm$ 10 per cent supply voltage variation with a frequency change of $\pm$ 2 Mc or less. Modulator circuitry for frequency modulating the oscillator was developed.

It was not possible, however, to meet the requirements of less than $\pm$ 2 Mc frequency variation over an ambient temperature range of -55°C to +75°C. Although the current regulator could be compensated to maintain nearly constant current, the change in frequency of the oscillators at constant current was so great that temperature compensation appeared to require an extensive effort. For this reason RCA suggested that the final three developmental models be transistor-oscillator multipliers.

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13. ABSTRACT (Continued)

B. TRANSISTOR-OSCILLATOR-MULTIPLIERS

1. Gun Probe Sonde

A transistor-oscillator-multiplier was developed using the RCA type 2N3553 overlay transistor simultaneously as a 437-Mc oscillator and as a variable capacitance frequency quadrupler. The device gives a 1750-Mc power output of 100 mw at 15 volts supply voltage or 250 mw at 20 volts. The TOM may be frequency modulated at frequency deviations up to 2 Mc by applying a small voltage to the base of the transistor.

One TOM unit was acceleration tested by the Ballistic Research Laboratories. The unit performed satisfactorily with little change in characteristics after being fired at 15,000-g acceleration. After a second firing at 37,000 g, however, the unit failed because of the opening of the leads in the transistor. A small number of the transistors had previously tested satisfactorily after being fired at 50,000 g. Further tests of both transistors and TOM units will be required to determine the acceleration capability. Two additional TOM units have been delivered to BRL for testing.

2. Standard Radiosonde Units

Typical transistor-oscillator-quadrupler units gave 300 to 400 milliwatts of power at 10 per cent efficiency over the 1660- to 1700-Mc tuning range. The frequency change with a $\pm$ 10 per cent supply voltage change was about 10 Mc. A simple series transistor voltage regulator reduced this change to less than 1 Mc. Positive temperature coefficient resistors and negative temperature coefficient capacitors were used to temperature compensate the unit reducing the frequency variation over a -55°C to +75°C from 25 Mc or greater to less than 4 Mc. The units can be frequency modulated at frequency deviations up to 2 Mc by a small voltage applied to the base of the transistor. The pulling figure for 1.5 VSWR was 2 Mc or less for all units tested.

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1 Jun 1962 - 31 Dec 1964

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AMSEL-RD-PF (Reports Distribution Unit)	1
AMSEL-RD-PF (Mr. V.J. Kublin)	1
AMSEL-RD-SMS (Mr. A. Peterson)	1
AMSEL-RD-PI	2
AMSEL-RD-PFS	1
AMSEL-RD-PFM	1
AMSEL-RD-PFM (Mr. I. L. Chase)	5
AMSEL-RD-P	1

This contract is supervised by the Solid State & Frequency Control Division, Electronic Components Department, USAEL, Ft. Monmouth, N.J. For further technical information contact Mr. I.L. Chase, Telephone 535-2352.

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